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A COMPARISON OF LONG SHOT AND EARTHQUAKES

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ERRATA

page 1	line 14	"of the"	should read "at the"
page 2	line 22	"et at"	should read "et al"
page 6	line 14	"unifed"	should read "unified"
page 9	line 25	"effect"	should read "effects"
page 68	line 6	"large"	should read "larger"

ABSTRACT

The seismic signal generated by the underground nuclear explosion, Long Shot, has been compared with seismic signals of earthquake origin and found to be similar on a regional scale. Negative Long Shot magnitude residuals are associated with areas of recent tectonic activity as are late arrivals, while positive Long Shot magnitude residuals and early arrivals have been found to be associated with tectonically stable regions. These trends are coincident with those indicated by data from other seismic events.

The more detailed comparison of Long Shot and earthquake magnitude residuals at Penticton and Fort St. James indicates that the Long Shot residuals also reflect the location of the source. At these stations, earthquakes with distances and azimuths comparable to Long Shot exhibit magnitude residuals that are most similar to those of Long Shot. The magnitude residuals of the University of British Columbia exhibit the same dependence on source parameters although a direct comparison with Long Shot could not be made. An examination of earthquake travel time residuals at Penticton and Fort St. James also indicates the same dependence on source location.

Long Shot surface waves indicate an average unified magnitude of 5.1 at Canadian stations as compared with an average unified magnitude of 6.0 from body waves at the same stations.

The comparison of the power spectra of Long Shot and earthquakes at Leduc and Victoria indicates relatively more energy at high frequencies from Long Shot than from earthquakes. This variation in spectral decrement is interpreted as an effect of the different source mechanisms.

The spectrum of Long Shot at Rocky Mt. House appeared to

be anomalous as it had a significantly larger spectral decrement than at the other stations and was indistinguishable from the spectra of earthquakes recorded at Rocky Mt. House. The trend of the power spectra also appear to be partially determined by the crustal and upper mantle structure in the vicinity of the station. The effect of the source parameters and travel path is also indicated by a tendency for the spectral decrement to increase with increased distance to source and with increased depth.

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CHAPTER I

INTRODUCTION

1-1 Long Shot

Long Shot was an underground nuclear explosion whose relevant source parameters are given by Clark (1965) as:

DATE	October 29, 1965
TIME	21:00:00.08 Universal Time
LOCATION	Amchitka Island, Aleutians Latitude 51°26'17" Longitude 179°10'57"
DEPTH	2300 feet below surface
ELEVATION	-2164 feet
FORM OF SHOT	80 kiloton TNT - equivalent nuclear device

The purpose of Long Shot was to provide data to further the ability to detect and locate nuclear explosions and to distinguish them from earthquakes at long range.

The reasons for the importance of this experiment have been summarized by Frosch (1965). Prior to this event, most controlled underground tests had been conducted in the continental United States. Since this is near some of the best instrumented regions in the world, most of the stations were too close to the events to take advantage of the third zone where the character of the source can be seen relatively undisturbed by the transmission path. The choice of Amchitka as the test site placed most of North America in this 25-90° range.

This area is seismically and tectonically comparable to Kamchatka and the Kuril Island regions where between 60 and 75 per cent of the earthquakes in the Soviet Union occur. These would constitute the majority of the seismic events, occurring in Communist

countries, which would have to be examined for the presence of explosions with the present distribution of nuclear technology.

The island arc structure exemplified by the Aleutians is one of strong anomaly in the structure of the earth's crust and upper mantle. It is therefore of great interest to determine the travel time bias, if any, introduced by this structure so that regional corrections might be made to standard travel time curves which will facilitate the accurate location of events in this region. The effect of anomalous crustal and upper mantle structure on the character of the signal is also of interest.

The usefulness of Long Shot is further enhanced by the large number of earthquakes of comparable magnitude that occur in this region. This allows a direct comparison of a nuclear explosion and earthquakes from the same region.

What was perhaps the final factor in establishing the value of this experiment was the high quality of both the special recording instrumentation used and the records obtained.

1-2 Summary of Available Long Shot Data

A pilot analysis of the Long Shot arrivals recorded by the 24 stations of the Canadian seismic network and a more comprehensive analysis of data from the 5 special stations operated by the Arctic Institute of North America is reported by Jensen et at (1966).

These records were examined to determine if the first motion of the P wave was compressional, if the surface wave magnitudes were small compared to P wave magnitudes, and if the shear wave amplitudes were small - characteristics which have been

suggested as criteria for distinguishing underground explosions from earthquakes. The signal to noise ratio was not always high enough to unambiguously determine the direction of first motion. Where the first motion could be determined, only Flin Flon appeared to be dilational. The low amplitude surface waves observed at 5 stations yielded a unified magnitude of 5.3 compared to the P Wave magnitude of 6.0. The lack of shear phases was consistent with the symmetric model of an explosive source.

The calculated body wave (unified) magnitude tended to increase with distance from the source. The magnitudes in British Columbia were lower than those at northern Canadian stations at the same distance.

The observed P wave, Jeffreys-Bullen travel time residuals were consistently negative with the largest residuals at the most distant stations. Further, the time residuals in British Columbia were small with respect to northern Canadian stations at the same epicentral distance.

Finally, power spectra were calculated from the high resolution, special station records at Leduc, Rocky Mountain House, Wawa and Victoria. These spectra exhibited common peaks at 1.2 to 1.4 and 2.2 to 2.4 cps separated by a trough at 1.9 cps. A comparison of the spectral amplitude decrement of the vertical component of the P wave arrival showed that the attenuation of the higher frequencies was significantly greater at Victoria than at the other stations.

Clark (1965) has published an analysis of the Long Shot data recorded by the LRSM (Long Range Seismic Measurement) stations and the VELA observatories as well as a preliminary summary of

the data reported by other permanent and temporary seismographic stations. He tabulated unified magnitudes, the maximum amplitudes of Pn, P, PcP and surface wave phases as well as Pn, P and PcP travel times for these stations. This data supports that of Jensen et al (1966) in indicating that the amplitude and time residuals in British Columbia and surrounding areas were anomalous with respect to the rest of North America.

Liebermann et al (1966) report their study of the relative excitation of body and surface waves by Long Shot and 29 earthquakes which occurred in the same geographic and tectonic region. Their analysis of the Long Shot records from 56 stations indicates that the surface wave generation by Long Shot was significantly less than that of earthquakes of comparable unified magnitude. This result is in agreement with previous studies of underground nuclear explosions. However, they list surface wave magnitudes at 16 Canadian stations as opposed to 5 stations reported by Jensen et al (1966).

1-3 Thesis Investigation

The Long Shot magnitude and time residuals are assessed in terms of the tectonic framework and local geology of the stations. Particular emphasis is placed on a comparison with earthquake residuals and on the Long Shot residuals observed in central British Columbia and the southern Yukon which appear to be anomalous with respect to the rest of North America. The spectra of the Long Shot arrivals in this anomalous area are determined and compared with Long Shot spectra from stations outside of the region. The spectra of earthquakes recorded at Leduc, Rocky Mountain House and Victoria are

compared with Long Shot spectra.

The long period records of the Canadian network stations are re-examined in an attempt to reduce the discrepancy between the number of surface wave observations reported by Liebermann et al (1966) and Jensen et al (1966). A summary of this work has been published by Currie et al (1967).

CHAPTER II

MAGNITUDES AND MAGNITUDE RESIDUALS

2-1 Introduction

The recorded amplitudes of seismic events are dependent on several factors

(i) source magnitude
(ii) source mechanism
(iii) epicentral distance
(iv) transmission properties of the material through which the signal propagates
(v) the seismometer characteristics

These factors must be accounted for if an accurate intercomparison of station responses is to be made.

The use of unified magnitudes (Gutenberg and Richter, 1956) provides a method of equalizing the effects of many of these variables. Unifed magnitude is defined as

$$m_b = Q + \log kA/T$$

where: Q = parameter depending on focal depth and epicentral distance

A = maximum vertical ground amplitude (zero to peak) of the body wave in microns

T = corresponding period in seconds

k = ground factor appropriate to the station

Q describes the P wave amplitude as a function of distance and source depth for a representative earth model. The ratio, A/T, is used since it is proportional to velocity and hence simplifies the formulation of direct magnitude-energy relationships. Also, it is found empirically that the use of this ratio, rather than amplitude, tends to minimize the systematic errors in the determination of a magnitude.

If the U.S.C.G.S. magnitude determination is considered in some sense to be the actual magnitude of the event, the difference between it and the calculated magnitude yields the magnitude residual, $- \log k_i$. The interpretation of these residuals is limited by the assumption of a valid amplitude - distance relationship and the U.S.C.G.S. definition of magnitude.

The U.S.C.G.S. magnitude of the events considered was defined as the logarithm to the base 10 of the average of the $(A/T) \times 10^Q$ values. Individual values which deviate from the average by the equivalent of 0.7 units of magnitude at any point in the computation or which are associated with P wave readings having residuals greater than 10 sec are not used.

This procedure has been discussed by Friedmann (1967). Using statistical arguments, she concludes that it leads to estimates which consistently underestimate the magnitude of large earthquakes and may overestimate the magnitude of small events. The best estimate of the mean is the average of the logs rather than the log of the average which will tend to be larger than the best estimat . She also observes that the truncation procedure will tend to bias the calculation of magnitude as the fraction of contamination will tend to increase as the magnitude decreases making the U.S.C.G.S. estimate of large events too large.

Another limitation on the usefulness of the U.S.C.G.S. magnitude as a standard is the uncertainty in any statistical estimate of a population mean. The U.S.C.G.S. magnitude may be determined by the average of as many as 30 stations or from the reading made at a single station. Despite these limitations,

magnitude residuals defined in terms of the U.S.C.G.S. magnitude are a useful and accepted basis for the intercomparison of stations and seismic events.

A magnitude residual incorporates the effects of differences due to source radiation patterns and deviations from an average transmission path. To separate these effects at a particular station, the mean of a large number of earthquake magnitude residuals is used to define the station correction

$$\log k = \sum_{i=1}^{N} \frac{\log k_i}{N}$$

This procedure is based on the assumption that the effects of the asymmetric source and near source crustal and upper mantle structure will be minimized by considering means. The realization of this assumption depends on a random orientation of fault planes and data that is well distributed in azimuth and distance. Neither of these conditions is likely to be met due to the limited number and concentration of seismically active regions in the world. However, if these assumptions are approximated, the station correction should indicate the effects of near station structure.

The interpretation of magnitude residuals from Long Shot is less complex because the source may be assumed to be symmetric. As such, these magnitude residuals will reflect deviations from an average transmission path. It is probable that part of this deviation is due to errors in the assumed amplitude-distance relationship. Chinnery and Toksöz (1967) have shown that their veloci -depth model of the mantle predicts deviations from standard amplitude-distance relationships for events in the Aleutian arc region but these changes are insufficient to explain the scatter

and the distribution of the Long Shot magnitude residuals.

This view is supported by Jordan et al (1965) who suggest that regional changes in the geophysical nature of the crust and upper mantle in the vicinity of the station can play an important part in modifying amplitudes relative to the standard amplitude-distance relationships. They contoured Pn and P wave maximum amplitude patterns over the United States from a number of seismic events both within and outside of North America and found persistent, anomalously low seismic amplitudes which were associated with regions of recent tectonic activity and high amplitudes associated with deep sedimentary basins and tectonically stable areas. Pasechnick (1962) reports the P wave amplitude variations in the U.S.S.R. from nuclear explosions at teleseismic distances. The regions of high and low amplitude that he notes are consistent with the amplitude-tectonic relationship exhibited by data in the United States.

Deviations from a standard transmission path may also be due to the crust and upper mantle in the vicinity of the source. Ichikawa and Basham (1965) find empirically that magnitude residuals depend on the source location as well as the nature of the crust and upper mantle near the receiver. This may be an indication of such a source effect.

In summary, the observed Long Shot residuals should incorporate deviations from the standard amplitude-distance relationships as well as possible effect of anomalous crust or upper mantle in the vicinity of the source or receiver. Station corrections determined from earthquakes should be most strongly influenced by the crust and upper mantle in the vicinity of the

receiver.

In an attempt to investigate the relative contributions of these factors and the validity of the assumptions involved, magnitude residuals are examined from several viewpoints.

The Long Shot data are compared with other magnitude data to determine its consistency with previously observed trends of high and low magnitude residuals.

Earthquake magnitude residuals are calculated for Fort St. James (FSJ), Penticton (PNT) and the University of British Columbia (designated UBC) stations for a more detailed comparison with the Long Shot residuals in these regions which appear anomalous. Particular emphasis is placed on the contribution of local effects to the observed magnitude residuals at these stations as well as the dependence, if any, of the residuals on the source parameters.

The final aspect of magnitude determination considered is the use of surface rather than body wave magnitudes. It has been found that the surface wave magnitude of an explosion tends to be significantly smaller than that of shallow earthquakes of the same body wave magnitude. As this difference has obvious possibilities as a discrimination technique, the relationship between the Long Shot body and surface wave magnitude (at Canadian stations) is also considered.

2-2 Long Shot Magnitude Residuals

The extent to which the Long Shot P wave arrivals were anomalous can be seen in Fig. 1 where the magnitude residuals are plotted as a function of epicentral distance. Negative magnitude residuals indicate particle velocities less than expected and

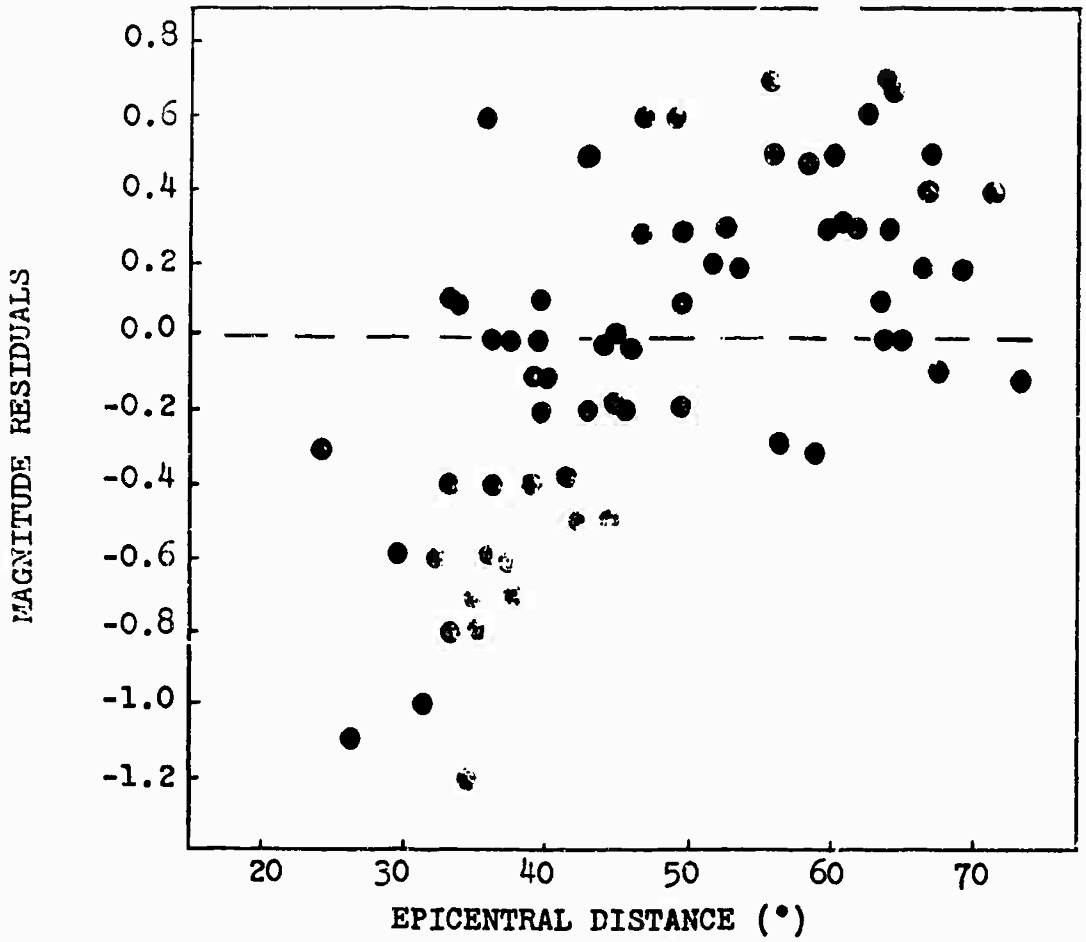


FIG. 1. Long Shot magnitude residuals at North American stations as a function of epicentral distance. Residuals after Jensen et al (1966) and Clark (1966).

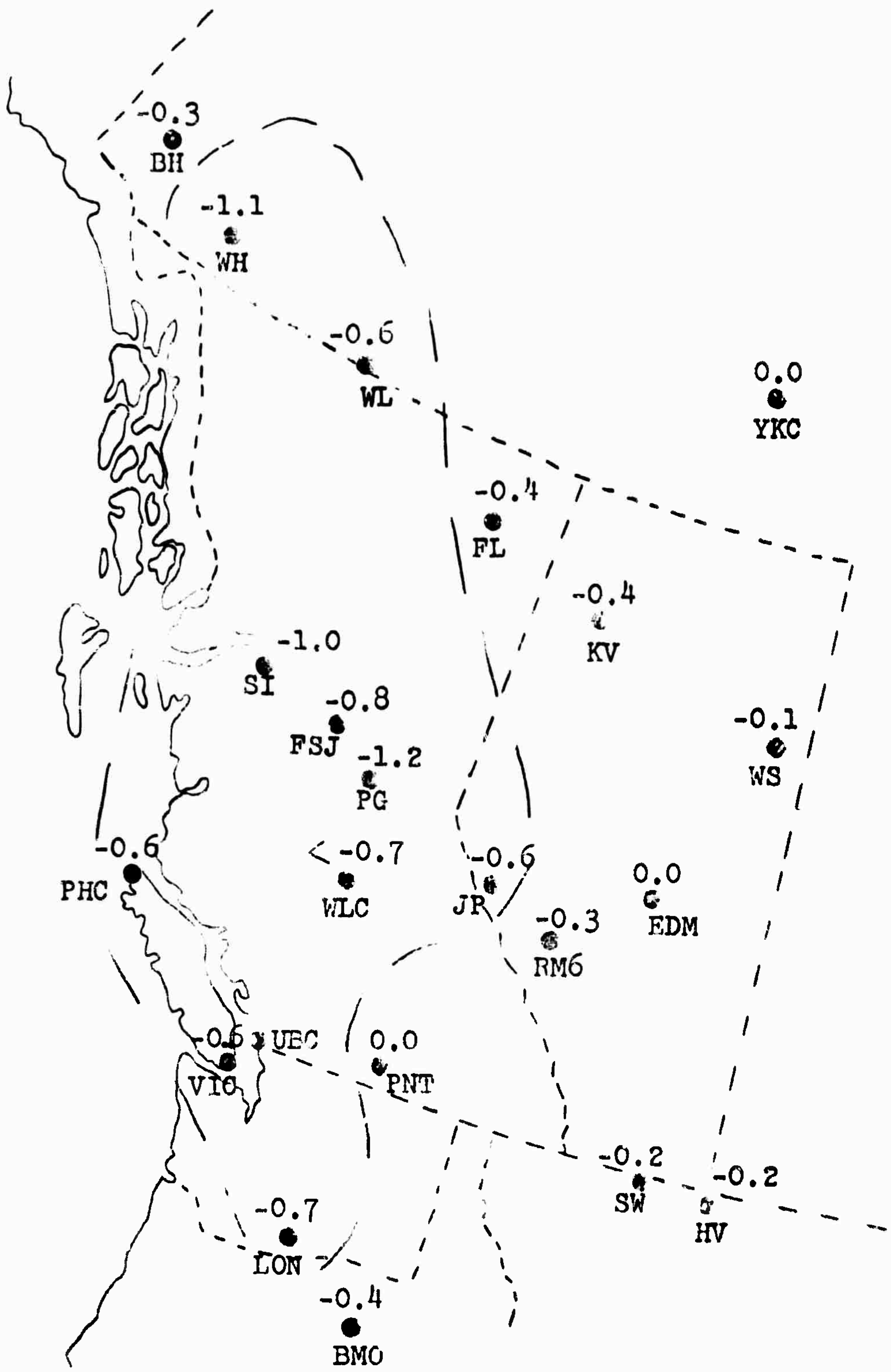


FIG. 2. Geographical distribution of anomalous Long Shot magnitude residuals.

positive residuals, particle velocities greater than expected on the basis of standard amplitude-distance relationships. The average magnitude residual of the stations within 45° of the source is negative whereas the average magnitude residual beyond 45° is positive. Anomalously negative residuals are found in the 25-35° range. The geographical distribution of these magnitude residuals defines the area of particular interest - a region in central British Columbia and the southern Yukon (Fig. 2).

The Chinnery and Toksöz (1967) model of the mantle based on data from the same azimuth predicts a relative minimum in amplitude in the 30-35° range and as such is compatible with this Long Shot data. However, to account for the observed magnitude residuals in the anomalous region, the Q values of Gutenberg and Richter (1956), which incorporate a low in this range, would have to be in error by 1 unit which corresponds to a predicted A/T ratio 10 times too large. For this reason it is unlikely that errors in the standard amplitude-distance relationship used to define unified magnitude will, alone, account for the observed Long Shot residuals and local conditions will contribute.

The importance of local and regional factors can be best determined by comparing the Long Shot residuals with other magnitude data. Fig. 3 shows the geographical distribution of the Long Shot residuals and the major tectonic divisions of North America (after Eardley, 1962).

Stations in the recent, western orogenic belts have an average magnitude residual of -0.41 which indicates anomalously low amplitude. Near average response is indicated at stations

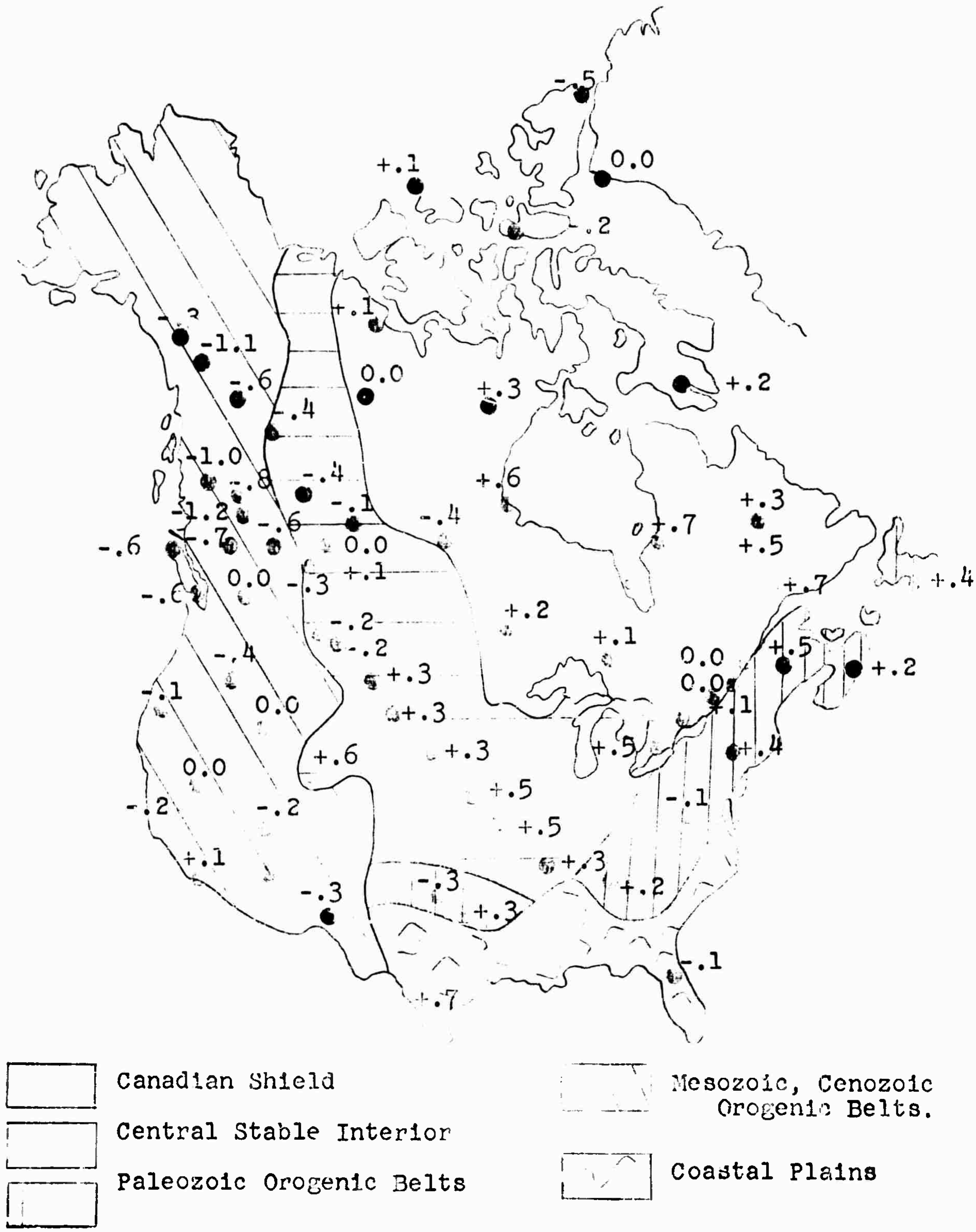


FIG. 3. Long Shot magnitude residuals and the major tectonic divisions of North America. Magnitude residuals from Clark (1966) and Jensen et al (1966).

in the central stable region with an average magnitude residual of +0.12. High amplitudes are associated with the older (Paleozoic) orogenic belts of the eastern and southern United States, average residual +0.20, the shield, average residual +0.23; and the coastal plains, average residual +0.30.

Although the average magnitude residual in the Paleozoic orogenic belts would have been expected to be less than that of the central stable region on the basis of the amplitude zoning suggested by Jordan et al (1965), the Long Shot residuals exhibit the same trends as other magnitude data and as such they must be partially attributed to regional factors.

Earthquake magnitude residuals calculated by Ichikawa and Basham (1965) at 10 Canadian stations offer an opportunity for direct comparison with the Long Shot magnitude residuals. At all of these stations, the mean earthquake residuals are at least as large as the Long Shot magnitude residuals (Table 1). If the station correction (-mean residual) does, in fact, incorporate the effects of the crust and upper mantle in the vicinity of the station, the observed Long Shot residuals must have been partially determined by other factors. This difference has the same sign at every station which suggests that the additional loss of amplitude indicated by the Long Shot residuals is probably a source effect as errors in standard amplitude-distance relationships would be expected to both overestimate and underestimate amplitude depending upon distance from source. However, the difference between the Long Shot residuals and the station corrections varies from station to station which indicates that lateral changes in the crust and

Table 1

Long Shot and Earthquake Magnitude Residuals*

STATION	Long Shot	earthquake mean	Kurils Kamchatka	Aleutians Alaska	South America	Mid Atlantic Ridge
Edmonton	0.0	+0.4	+ .5	+0.4	+0.5	+0.6
Halifax	+0.2	+0.3	+ .2	+0.3	+0.4	+0.2
London	+0.5	+0.5	+ .3	+0.5	+0.5	+0.5
Montreal	0.0	+0.2	0.0	+0.2	+0.4	+0.1
Mould Bay	+0.1	+0.1	-0.2	+0.2	+0.3	0.0
Ottawa	+0.1	+0.3	0.0	+0.4	+0.2	+0.3
Penticton	0.0	+0.2	+0.1	+0.1	+0.4	+0.2
Port Hardy	-0.6	0.0	+0.1	-0.1	0.0	+0.4
Shawinigan Falls	+0.3	+0.3	-0.1	+0.3	+0.3	+0.5
Victoria	-0.6	+0.2	+0.1	+0.0	+0.3	+0.7
mean difference between Long Shot & earthquakes		+0.21	+0.10	+0.27	+0.33	+0.35

* Long Shot residuals are after Jensen et al (1966) and the earthquake residuals after Ichikawa and Basham (1965).

upper mantle in the vicinity of the source and receiver may also have affected the signal. This comparison also indicates a large regional variation (Table 1). The mean difference between the Long Shot and earthquake residuals is +0.21 but if the sample is restricted to earthquakes in the nearby Kurils-Kamchatka region, a mean difference of only +0.10 is obtained. The mean difference in magnitude residuals for other regional samples ranges from +0.27 to +0.35. This indicates that the observed Long Shot magnitude residuals have been influenced by the geographical location of the source.

Not only may the Long Shot and earthquake residuals be compared on a regional and station to station basis but also in terms of the scatter of magnitudes. A priori, the symmetric nature of the explosive source suggests that the variation in magnitudes calculated from it should be small relative to earthquake determinations. Carpenter (1965) has suggested that the difference between the scatter of magnitudes from the two sources, if it exists, may be a useful diagnostic technique.

Comparisons of this kind are most conveniently made by histograms of the magnitude residuals. Fig. 4 shows histograms of teleseismic magnitude residuals from earthquakes in the Aleutian Arc region (Table 2), the Long Shot data and typical explosions (Carpenter, 1965). All the data is from North America stations. The earthquake histogram is the average of the events listed in Table 2 from U.S.C.G.S. Earthquake Data Reports. The truncation procedure of the U.S.C.G.S. already discussed was not used in the determination of this histogram. These histograms

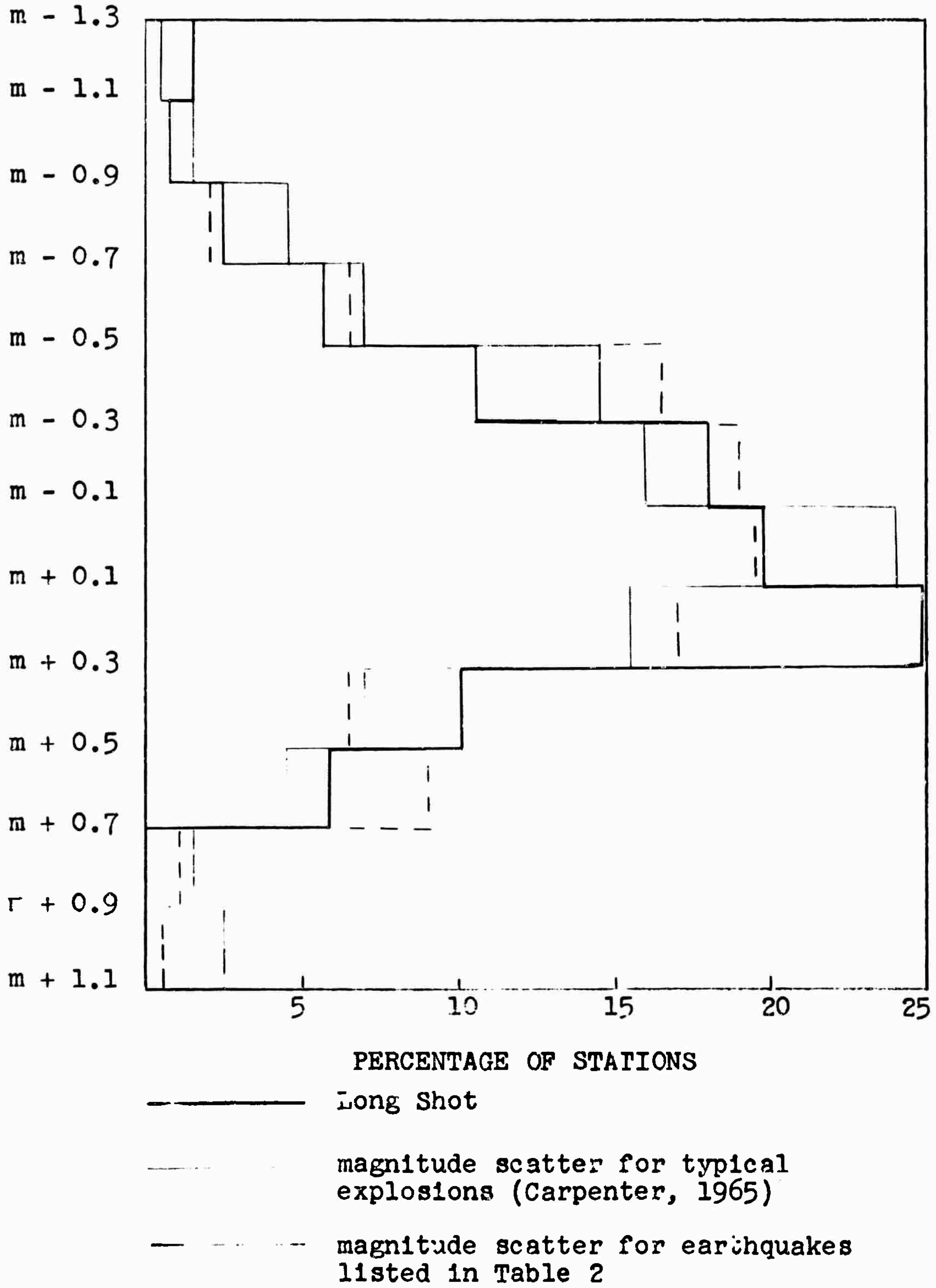


FIG. 4. Histograms of magnitude scatter for earthquakes, Long Shot and explosions.

Table 2

Earthquakes* used in Histogram

DATE	LAT	LONG	DEPTH	MAG
July 29, 1965	51.07N	171.30W	Normal	5.5
Sept. 2, 1965	51.90N	175.47E	31	5.6
Sept. 4, 1965	46.61N	153.47E	27	5.5
Sept. 4, 1965	58.21N	152.62W	19	6.1
Sept. 8, 1965	57.53N	152.14W	25	5.6
Oct. 1, 1965	50.11N	178.25E	32	6.3
Nov. 18, 1965	53.86N	160.67E	12	6.0
Dec. 5, 1965	52.59N	173.19E	33	5.5
Dec. 13, 1965	44.70N	150.12W	35	5.7
Jan. 22, 1966	55.97N	135.69W	33	5.8
Feb. 6, 1966	60.37N	152.35W	91	5.3
April 11, 1966	56.65N	151.97W	Normal	5.4
May 11, 1966	48.86N	156.21E	39	5.8
May 11, 1966	48.77N	156.31E	28	5.7
May 15, 1966	51.48N	178.44W	31	5.8
July 4, 1966	51.74N	178.89E	71	6.2
July 4, 1966	51.81N	176.42E	28	5.7

*U.S.C.G.S. determinations

indicate that the Long Shot data is skewed relative to the other explosions and the earthquakes but the maximum deviations are almost the same.

The scatter of magnitude determinations may be compared quantitatively by considering standard deviations. Clark (1965) gives a unified magnitude of 5.94 $\pm$ 0.46 from the LRSM stations at teleseismic distances. This standard deviation is about 0.1 units larger than that commonly observed from Nevada Test Site events. The standard deviations in magnitude of the earthquakes considered (Table 2) range from $\pm$ 0.26 to $\pm$ 0.80 with an average value of $\pm$ 0.43.

In terms of earthquakes in a comparable region, this very limited sample gives no indication that the Long Shot residuals observed in North America reflect the fact that it was a nuclear explosion. It has also been found that the Long Shot residuals are generally consistent with amplitude distributions from other sources. Finally, there is a strong indication that the geographical location of Long Shot affected the observed residuals. For these reasons, the anomalous region in central British Columbia and the southern Yukon indicated by Long Shot is investigated in terms of the earthquake magnitude residuals observed there.

2-3 Earthquake Magnitude Residuals

Penticton, Fort St. James and the University of British Columbia seismic stations were chosen for further study because the Long Shot data (Fig. 2) indicated that they were representative of substantially different regions. Long Shot magnitude residuals of 0.0 and -0.8 were observed at Penticton and Fort St. James so

they were considered as normal and anomalous stations respectively. Magnitude residuals at the University of British Columbia are of interest because two stations in comparable tectonic environments, Victoria and Port Hardy, both exhibited anomalous Long Shot magnitude residuals of -0.6.

Station parameters are given in Table 3.

Table 3 Station Parameters

Station	Latitude	Longitude	Approx. Elevation
Penticton (PNT)*	49°19'N	119°37'W	550 m
Fort St. James (FSJ)*	54°26'N	124°15'W	700 m
University of British Columbia	49°19'N	123°15'W	100 m

* Canadian Dominion Observatory seismic network

The Penticton station is located in the White Lake basin on early Tertiary sediments of the White Lake formation which are dominated by the volcanic member. This formation is composed of pyroclastic rocks, volcanic breccia, volcanic sandstone, conglomerate and some coal. These sediments are underlain by a series of Tertiary basalts (Marron formation, Church (1967)) which in turn lie on chertz quartzites that are probably Paleozoic in age. White and Savage (1965) give a crustal thickness of about 30 km in southern British Columbia with a P wave velocity of 5.9 km/sec and a Pn velocity of 7.8 km/sec.

The Fort St. James station is situated in the Fort St. James basin, a Pleistocene glacial-lake basin which is largely covered by glacial deposits. The calibration data for this station

(Mines and Technical Surveys) states that the vault is located on Paleozoic sediments. Geologic maps of the region (Armstrong, 1949) show Permian outcrops near the coordinates of the site, outcrops which are part of the Stuart Lake belt of the Cache Creek group. This group consists of a conformable succession of about 20,000 feet of interbedded limestone, ribbon chert, argillite, slate quartzite, tuft and breccia. These strata have been partially eroded and complexly folded. The Stuart Lake belt is underlain unconformably by the Wolverine complex of granitic gneisses and granites. The nearest crustal data is from Prince George, about 125 km southeast of the station. There, the crust is thought to be about 35 km thick with a velocity of 6.1 km/sec and a Pn velocity of 8.0 or 8.6 km/sec (W.G. Milne, personal communication).

The University of British Columbia is within what is known as the Georgia Depression (Armstrong and Brown, 1954). A hypothetical cross section (Johnston, 1923) shows unconsolidated Pleistocene sediments underlain by Tertiary strata. The Tertiary strata (Kitsilano and Burrard formations) are composed of sandstone, clays, conglomerate and shales. These lie unconformably on the Mesozoic granitic batholith structure that characterizes the Coast Range in this area. The crustal section under this station given by White and Savage (1965) is composed of 6 km at 5.9 km/sec, 45 km at 6.8 km/sec and a Pn velocity of 7.7 km/sec.

Penticton and Fort St. James short period vertical records for 1965 were examined. The short period records for November 1965 to September 1966 were examined from the University of British Columbia station.

Magnitude residuals were calculated if the arrival met a number of criteria. Only events whose peak to peak record amplitude was greater than one millimeter were used. The arrival had to be sufficiently impulsive that the maximum P wave amplitude could be chosen from the first five cycles. Only arrivals within 5 seconds of the Jeffreys-Bullen travel time were used to reduce the probability of assigning the arrivals to the wrong source.

536 events satisfied these criteria at Penticton, 211 at Fort St. James and 81 events at the University of British Columbia. These numbers may be interpreted as a rough measure of the ambient noise levels at the stations although this is not a strictly valid comparison as FSJ and UBC were occasionally inoperative.

Unified magnitudes were calculated according to the formula of Gutenberg and Richter (1956) using linearly interpolated Q values from the 'Dawn' Tables (1964). Magnitude residuals were determined by comparing the calculated unified magnitude with the U.S.C.G.S. value.

The mean magnitude residuals obtained as well as the mean source parameters are shown in Table 4. The mean depth, magnitude, distance and azimuth of the events considered at the two stations indicate that a direct comparison of the mean residuals is probably valid despite the difference in sample size. The histograms (Figs. 5 and 6) and fitted normal curves show that the residuals tend to be normally distributed.

The station corrections are -0.17 ± 0.03 at PNT and $+ 0.14 \pm 0.05$ at FSJ for 95 per cent confidence limits. The PNT value agrees, within the confidence limits, with the value of

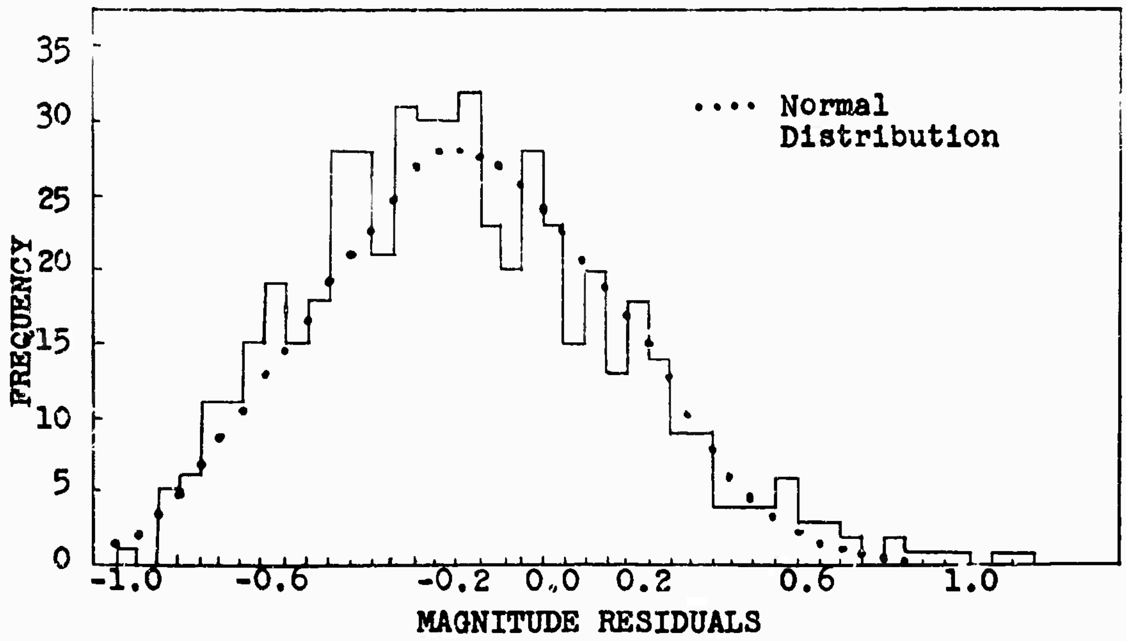


FIG. 5. Histogram of earthquake magnitude residuals at Penticton.

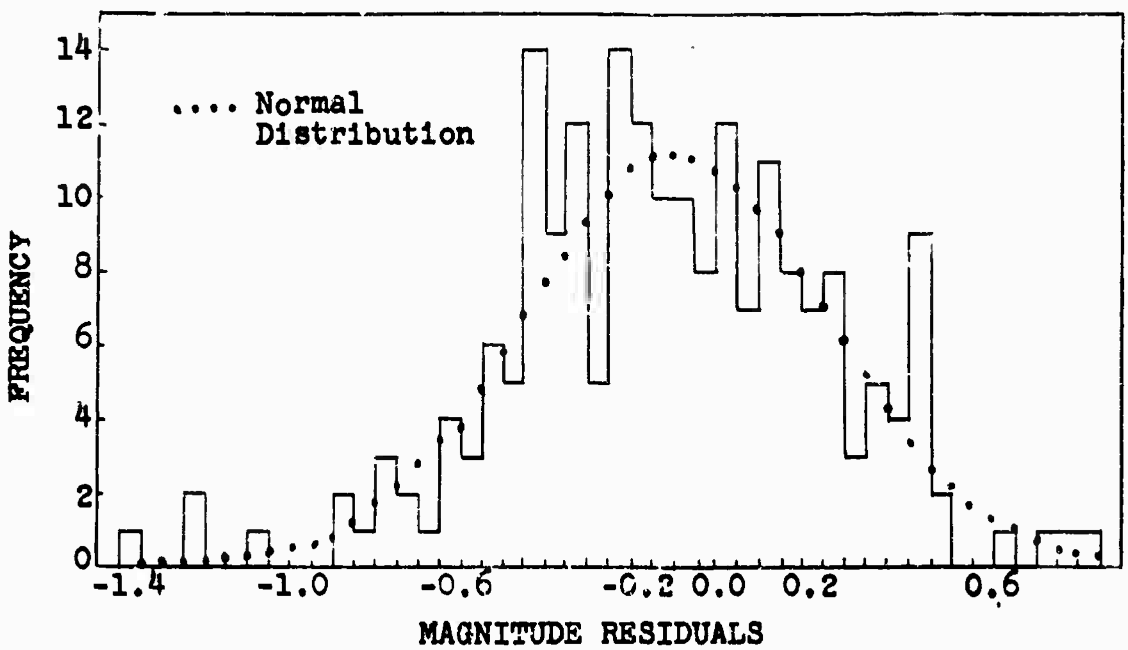


FIG. 6. Histogram of earthquake magnitude residuals at Fort St. James.

- 0.21 $\pm$ 0.03 determined by Ichikawa and Basham (1965) using different earthquakes.

TABLE 4 PNT and FSJ Magnitude Residuals

	PNT (536 events)		FSJ (211 events)	
	mean	st. dev.	mean	st. dev.
depth(km)	112.42	164.69	95.99	149.30
magnitude	5.25	0.51	5.45	0.48
distance°	58.95	24.98	55.38	26.31
azimuth°	241.83	75.05	239.59	87.96
mean residual	0.17	0.38	-0.14	0.36

TABLE 5 UBC Magnitude Residuals

	UBC (81 events)	
	mean	st. dev.
depth (km)	85.49	135.99
magnitude	5.78	0.41
distance°	55.66	30.89
azimuth°	255.28	77.99
mean residual	0.36	0.37

The mean source parameters (Table 5) of the events used to calculate the station correction at UBC are substantially the same as those for PNT and FSJ but the histogram of the magnitude residuals (Fig. 7) shows large departures from a normal distribution. The large positive residuals ($\Delta m_b > 1.2$) are all associated with events within 13° of the station. The station correction at UBC is - 0.36 $\pm$ 0.08 for 95 per cent confidence

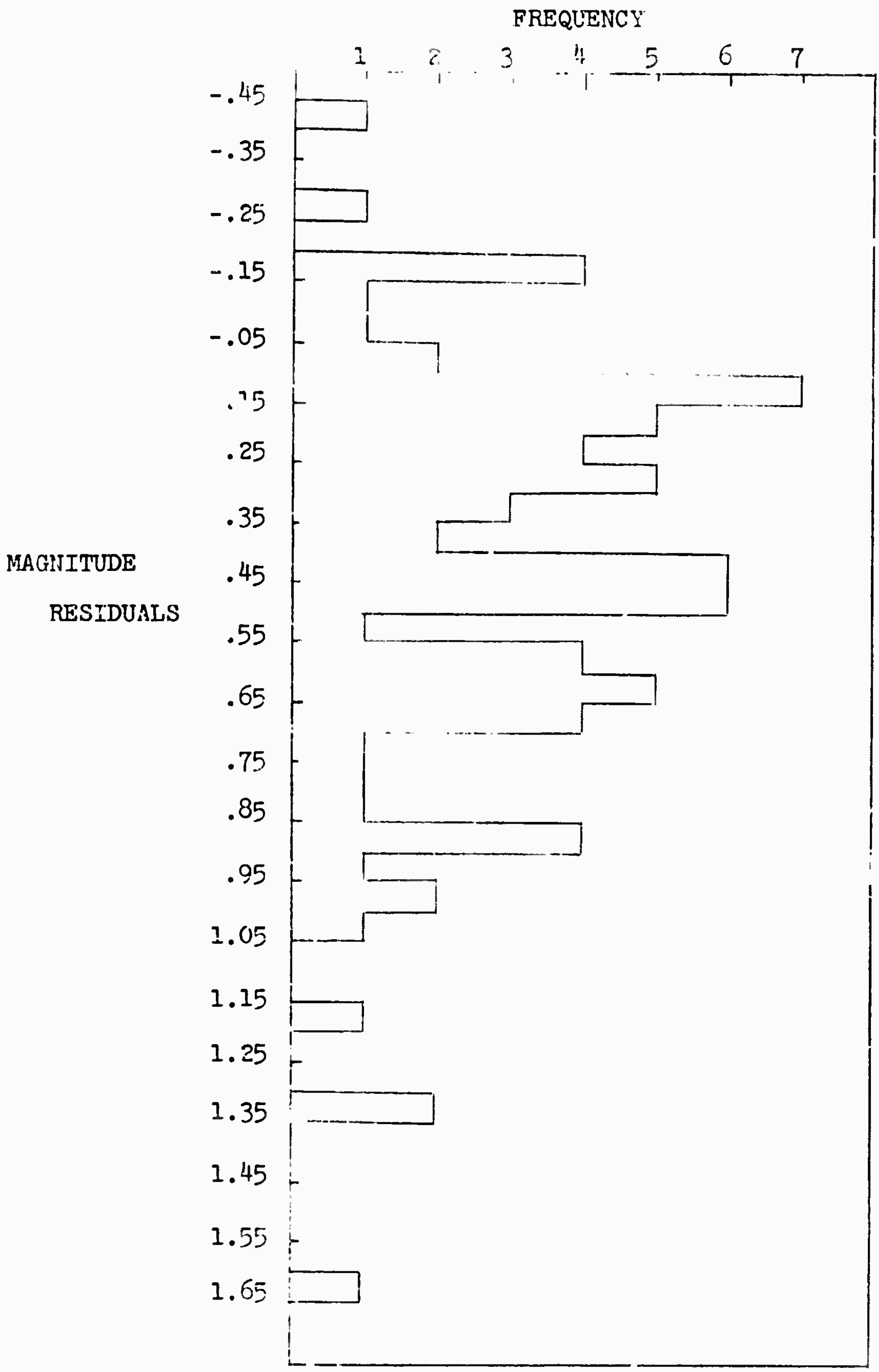


FIG. 7. Histogram of earthquake magnitude residuals at the University of British Columbia.

limits and assuming a normal distribution.

The mean magnitude residuals correspond to A/T ratios 1.5, 0.7 and 2.3 times the predicted value at Penticton, Fort St. James and the University of British Columbia respectively. As the period of the P wave arrival used to calculate magnitudes did not vary significantly from station to station, the differences can be thought of as differences in signal amplitude.

Part of this difference can be explained by considering the effect of the crust and surficial geology on the signal. Gutenberg (1957) noted that the seismograph records may largely indicate the vibrational characteristics of the surface material rather than the earthquake. He observed amplitudes 10 times as high on saturated, unconsolidated material as on crystalline material from the same event.

Formally the problem is to determine the motion of the surface from a seismic wave striking the base of the crust but it is usually simplified by considering the response of a horizontally stratified system to a sinusoidal plane wave striking the base at oblique angles of incidence. Despite this simplification, the technique yields valuable information about the response of an idealized crustal section.

The matrix formulation of the problem by Haskell (1953) and its application to P waves by Hannon (1964) makes it feasible to generate the transmission coefficients of a large number of crustal models. The transmission coefficients are the ratios of the surface particle velocities, horizontal and vertical, to the total particle velocity in the bottom layer due to the dilational wave in it.

These coefficients indicate that (Hannon, 1964)

(i) the effect of the crust varies with
  (a) crustal structure
  (b) angle of incidence
  (c) frequency

(ii) low velocity sedimentary surface layers can cause large amplitudes to be observed at the free surface

The sensitivity to low velocity sedimentary surface layers is particularly relevant to the UBC station which is situated on unconsolidated glacial sediments.

Vertical transmission coefficients have been calculated for crustal models at PNT, FSJ and UBC based on the geology of the stations discussed earlier (Table 6). Coefficients were calculated over the range 0.2 - 2.0 cps which is the range of periods of the maximum amplitude P wave arrivals used in the magnitude calculations. The average epicentral distance of about 60° corresponds to an angle of incidence of approximately 24°. The coefficients are shown as a function of frequency in Figs. 8, 9 and 10.

Table 6 Crustal Models at PNT, FSJ and UBC

Station	Thickness km	P velocity km/sec	S velocity km/sec	Density GM/cm^3
PNT	0.50	4.00	2.31	2.30
	1.00	4.70	2.71	2.50
	30.00	5.90	2.40	2.68
		7.80	4.50	3.04
FSJ	3.00	5.00	2.89	2.54
	32.00	6.10	3.52	2.72
		8.00	4.62	3.10
UBC	0.10	2.00	1.16	2.00
	1.40	3.90	2.25	2.35
	5.50	5.90	3.40	2.68
	45.00	6.80	3.92	2.83
		7.70	4.44	3.00

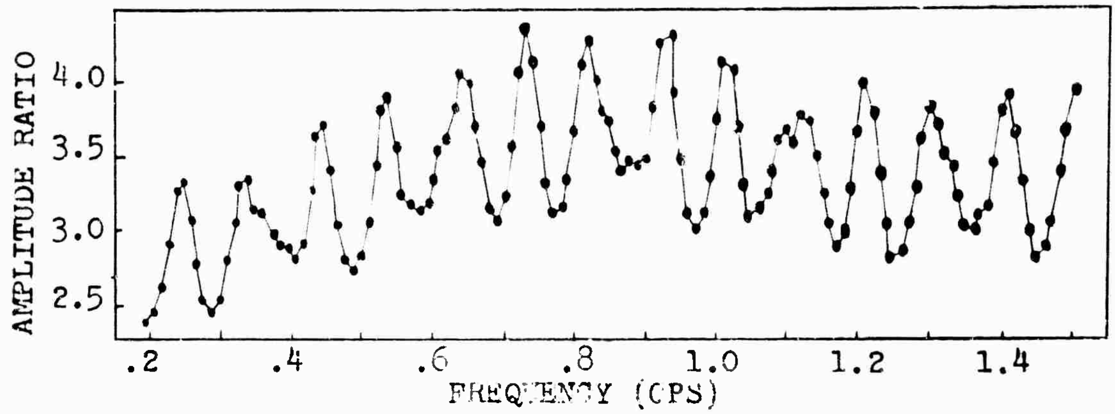


Fig. 8. Vertical transmission coefficients for a theoretical Penticton crustal model.

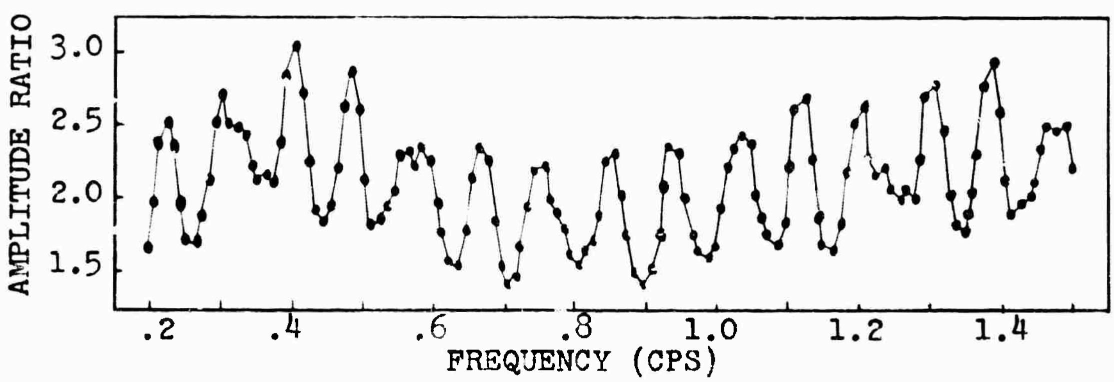


Fig. 9. Vertical transmission coefficients for a theoretical Fort St. James crustal model.

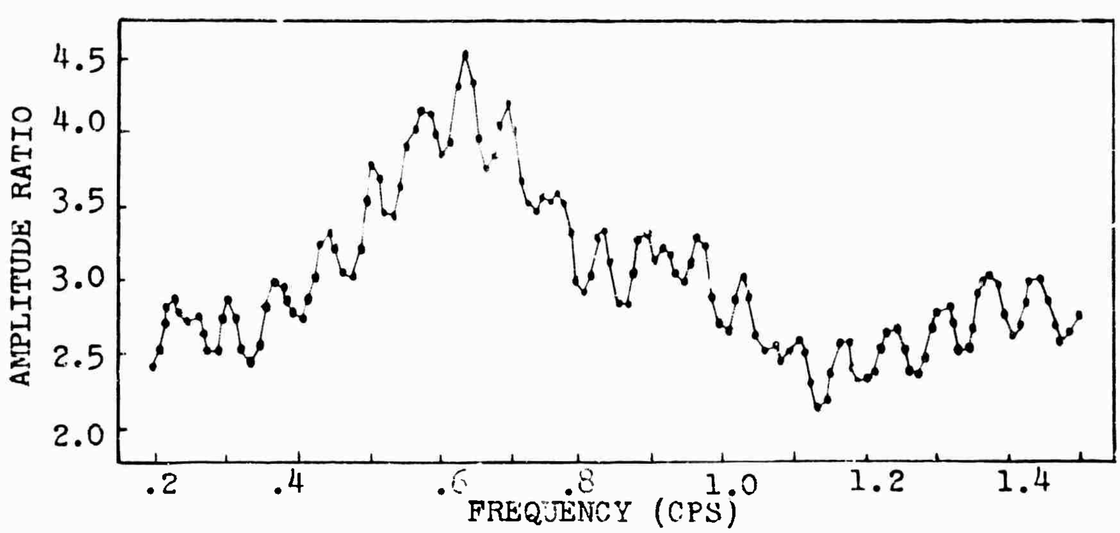


Fig. 10. Vertical transmission coefficients for a theoretical University of British Columbia crustal model.

These models appear to explain part of the amplitude differences between the stations. The relative amplitudes are in the right order, the mean amplitudes in the period ranges of interest are 3.64 at UBC, 3.06 at PNT and 2.47 at FSJ. It is important to consider relative amplitudes as most crustal sections produce amplification of the vertical component at most frequencies. However, the mean magnitude residuals indicate a greater difference in amplitudes than is exhibited by the transmission coefficients. In particular, the response at UBC should be 3 times that of FSJ whereas the transmission coefficients indicate a factor of 1.5. Part of this difference may be ascribed to limited knowledge of the actual crustal sections at these stations and part to the simplification of the actual crustal structures to a layered model.

The three stations also show a systematic variation with azimuth (Fig. 11). Despite the scatter of the points, all stations show an amplification in the first and third quadrants relative to signal amplitudes in the fourth quadrant. The strongest feature is the relative attenuation in the fourth quadrant which is the azimuth of the arrivals from the Aleutian arc. As this effect appears at all three stations, it may be a near source rather than a station effect. However, Rocard (1965) has interpreted azimuthal variations in terms of focusing seismic energy within the earth's crust, that is, a near station phenomena. He believes that a bending or tilting of the Mohorovicic discontinuity would produce the strongest effect. This suggestion may be applicable to these stations as the topography of the Mohorovicic discontinuity, in southern British Columbia at least, is known to be complex. Azimuthal variations may also be caused by lateral inhomogeneities in the vicinity of

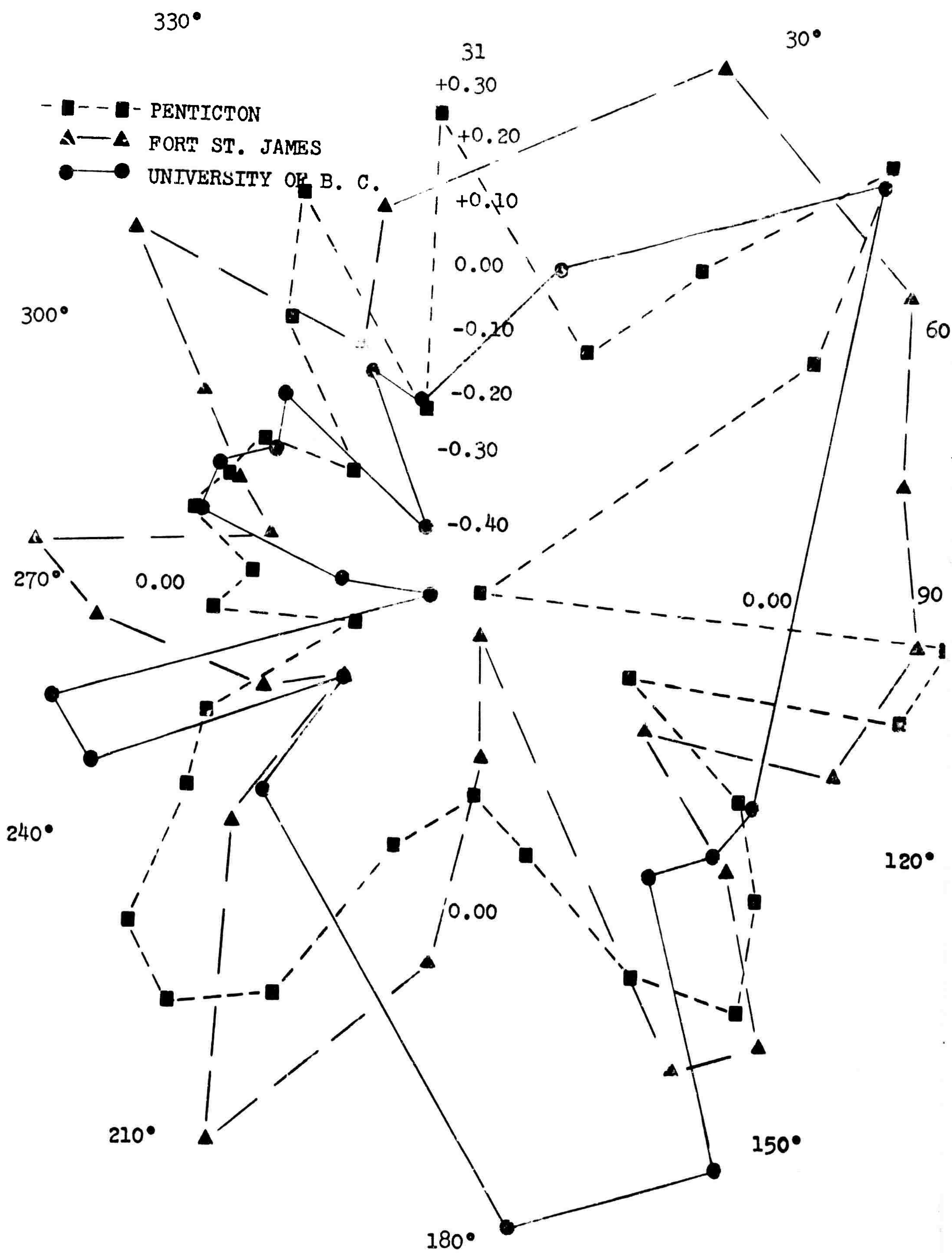


FIG. 11 Azimuthal variation in average magnitude residuals at PNT, FSJ and UBC.

the stations which will cause scattering.

The magnitude residuals at these stations also varied with epicentral distance. Fig. 12 shows the mean magnitude residuals in 5° intervals versus distance. The PNT and FSJ values should be more significant as they have larger samples in each interval than UBC. If the mean magnitude residual is considered as a constant bias introduced by local effects, all three stations exhibit a similar trend with distance. Near events ($\Delta < 15°$) are received with higher than average velocities as are events in the 45-65° range. Relative lows are indicated in the 20° and 70° regions. The consistency of these trends, depite the fact that different events are used at each station, suggests that these fluctuations represent inadequacies in the standard amplitude-distance relationship.

The effect of the local crust and upper mantle on the observed residuals as well as the variation of the residuals with distance and azimuth must be considered in comparing the Long Shot data with the earthquake residuals at these stations and in assessing the anomalous region indicated by Long Shot.

The mean magnitude residual of 0.36 $\pm$ 0.08 at UBC is markedly different than the Long Shot magnitude residuals of -0.6 observed at Victoria and Port Hardy which are in a comparable tectonic environment. However, the presence of a low velocity surface layer at UBC as compared with the gneiss at Victoria and massive volcanic rock at Port Hardy produces an amplification of the signal at UBC relative to that recorded at Victoria or Port Hardy. This local effect corresponds to a correction factor of

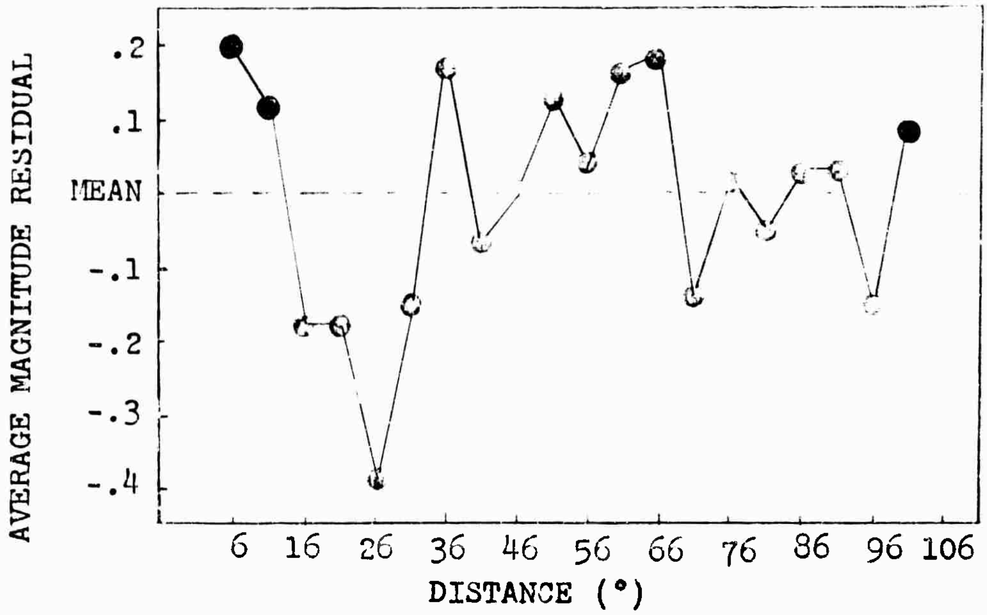


FIG. 12(a). Epicentral variation in average magnitude residuals at PNT.

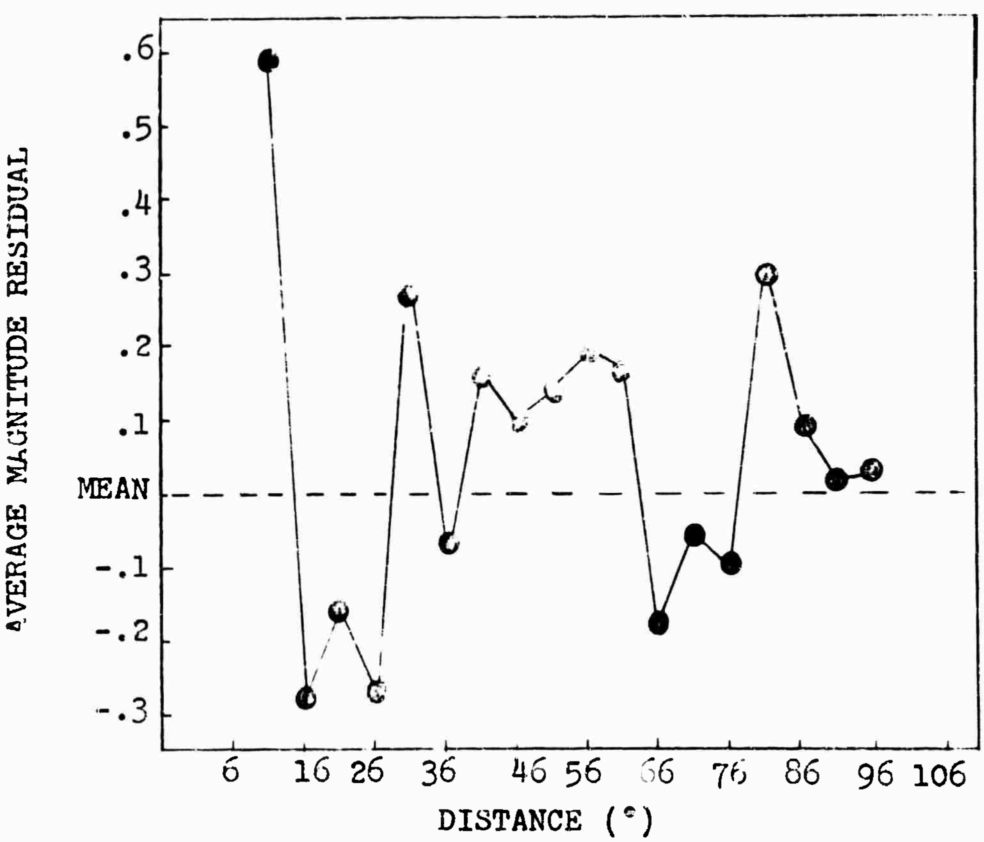


FIG. 12(b). Epicentral variation in average magnitude residuals at FSJ.

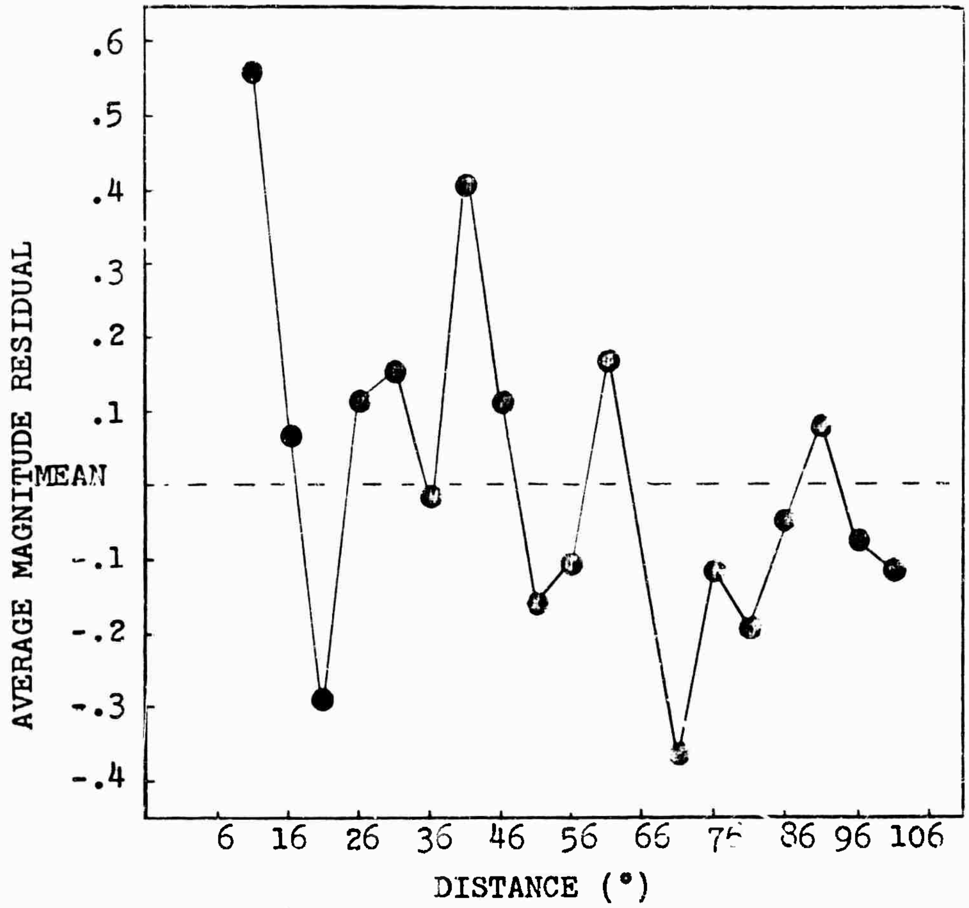


FIG. 12 (c). Epicentral variation in average magnitude residuals at UBC.

-0.3 which must be applied to the UBC station when comparing it to the Victoria and Port Hardy stations. Even with this adjustment, the corrected mean magnitude residual of +0.06 at UBC is still inconsistent with the Long Shot residual of -0.6 at Victoria. The earthquake magnitude residuals at UBC do, however, show a tendency to be less than the mean for events at the azimuth and distance of Long Shot. (Figs. 11 and 12).

The difference between the mean magnitude residuals and Long Shot residuals, -0.17 at PNT and -0.66 at FSJ, represents the loss of amplitude of the Long Shot arrival in excess of that normally observed at these stations. At least part of this is related to the geographical location of Long Shot as the magnitude residuals at both PNT and FSJ exhibit relative lows in the distance and azimuthal range of Long Shot (Figs. 11 and 12). The effect of source location is shown in Table 7.

Table 7 Earthquake Magnitude Residuals at PNT and FSJ versus Long Shot Magnitude Residuals at the same stations

	PNT	FSJ	PNT-FSJ
Long Shot	0.0	-0.8	0.8
USCGS magnitude 5.9 to 6.1	-0.04	-0.21	0.17
depth 0-20 km	0.14	-0.05	0.19
azimuth 292°-302°	0.08		
284°-294°		-0.28	0.36
distance 34-42°	0.15		
30-37°		-0.18	0.33
all values	0.17	-0.14	0.31
earthquakes at azimuth and distance of Long Shot	0.14	-0.23	0.37

In the cases considered, the mean magnitude residual at PNT is larger than at FSJ. This effect is largest for sources in the same epicentral and azimuthal range as Long Shot where a mean difference of +0.37 is observed as compared with a difference of +0.8 for Long Shot. Although this is not as large as the difference in Long Shot residuals at these stations, the effect of comparing a single set of readings and mean residuals from different sources must be considered.

If the sample is restricted to common sources with azimuths and distances comparable to Long Shot, a difference in residuals of 0.18 $\pm$ 0.13 is obtained between PNT and FSJ. Using two times the standard deviation as a measure of the scatter of the data, the range of differences in magnitude residuals is 0.18 $\pm$ 0.64. As 95 per cent of the data should fall within this range and since the Long Shot data does, it cannot be considered unexpected from a source in the Aleutian Arc region.

The mean magnitude residual of -0.14 $\pm$ 0.05 obtained at FSJ supports the Long Shot data in indicating that it is located in a region of low signal amplitude. Neither the mean magnitude residual of +0.36 $\pm$ 0.08 obtained at UBC nor the values of 0.21 $\pm$ 0.04 and 0.04 $\pm$ 0.05 given by Ichikawa and Basham (1965) for Victoria and Port Hardy respectively indicate that the coastal region is also part of a low amplitude region despite the relatively low Long Shot residual of -0.6 at both Victoria and Port Hardy. The mean magnitude residual of +0.17 $\pm$ 0.03 at PNT is consistent with the Long Shot data and indicates that it is not part of the low amplitude region despite gross similarities in regional geology.

The variation of the earthquake magnitude residuals with epicentral distance indicates that the anomalous Long Shot residuals may be partially explained by errors in the standard amplitude-distance relationships. The data at these stations indicates that the curves may be in error by as much as 0.2 units in the 25° range although this effect cannot, at this time, be separated from such possible factors as lateral inhomogeneities in the crust and upper mantle in the vicinity of the station or source. This also applied to the azimuthal variations of the magnitude residuals which indicate that events in the Aleutian Arc tend to be received with lower than average amplitude at all three stations.

To obtain an indication of how the observed magnitude residuals at these stations depend upon the source parameters, the data were analysed by the statistical technique of step wise linear regression (Draper and Smith, 1966). At all three stations, the only strong linear correlations were between the magnitude residuals and source magnitude and with azimuth. The magnitude residuals tended to decrease as these source parameters increased. This tendency is opposite to that suggested by Friedmann (1967) who suggested that magnitude residuals should increase with increased magnitude because of the U.S.C.G.S. definition of magnitude already discussed.

2-4 Long Shot Surface Waves

Liebermann et al (1966) reported the recognition of Long Shot generated surface waves at 16 Canadian stations compared with the 5 identifications given by Jensen et al (1966) after an examination of the records for the same stations. For this reason, the

long period records of the Canadian seismic stations were re-examined. Surface waves are now recognized at 12 stations plus tentative identifications at 2 stations (Table 8).

Table 8

Surface Wave Ground Amplitudes and Magnitudes

Station	Amplitude peak-to-peak (μ)	Surface wave magnitude: vertical M_s	Surface wave magnitude: horizontal M_s
Alert (ALE)	(0.89, 0.55, 0.66)*	4.2	4.2
Baker Lake (BLC)	(0.24, 0.24, 0.25)	3.6	3.8
Coppermine (CMC)	(0.94, 0.68, 0.83)	4.1	4.2
Flin Flon (FFC)	(0.66, - , 0.76)	4.1	4.2
Frobisher (FBC)	(0.60, 0.49, 0.42)	4.2	4.3
Great Whale (GWC)	(- , 0.63, 0.34)	-	4.3
London (LND)	(- , 0.42†, -)	-	4.1
Montreal (MNT)	(0.48, 0.66, 0.44)	4.2	4.5
Mould Bay (MBC)	(0.63, 0.55, 1.59)	4.0	4.4
Ottawa (OTT)	(0.89, 0.45, 0.43)	4.5	4.4
Resolute (RES)	(0.81, 0.51, 0.54)	4.1	4.1
Scarborough (SCB)	(- , 0.22†, -)	-	3.9
Schefferville (SCH)	(0.52, 0.45, -)	4.2	4.2
Yellowknife (YKC)	(1.69, 0.64, 1.18)	4.3	4.3

*Amplitudes are in the form (Z, N, E)

†Identification uncertain

The values given should be considered as upper limits to the Long Shot motion because the signal probably included surface waves from another source (Liebermann et al (1966)). An earthquake of magnitude 4 occurred at about 21:00:03 U.T. October 29, 1965 near Unalaska Island (about 53.5° N, 168° W). As it was closer to the Canadian stations than Long Shot (from 4-10°) and about 3 minutes later, the theoretical travel times are practically identical. The small magnitude of this earthquake indicates that its contribution to the total displacement would be small. Another constraint on the accuracy of the amplitudes given was the extremely low signal to noise ratio at many of the stations.

Where possible, the surface wave magnitude, Ms, has been calculated from the total horizontal displacement and from the vertical displacement (Table 8).

An extrapolation of the nomogram by Gutenberg and Richter (1956) was used to calculate Ms from the total horizontal displacement. This nomogram is based on the equation (Gutenberg, 1945):

$$Ms = \log A_H - \log B + C + D$$

where: A_H = horizontal component of the maximum ground displacement in microns for surface waves having periods of about 20 sec

$-\log B$ = parameter depending on epicentral distance (determined from Table 4 of Gutenberg (1945))

$C + D$ = correction factor for station and depth, taken as zero

Where only one component of the horizontal displacement was observed, the other component was assumed to be zero.

Ms was calculated from the vertical displacements using the equation (Båth, 1952):

$$Ms = \log A_z - \log B + \overline{\delta}(h) + M_r + c(M_o + M_{calc})$$

where: A_z = vertical ground motion in microns of surface wave of about 20 sec period

$-\log B$ = distance factor, from Table 4 Gutenberg (1945)

$\overline{\delta}(h)$ = depth correction, zero in this case

M_{calc} = sum of the first four terms

$c(M_o - M_{calc})$ = correction factor to make Ms values consistent with those obtained from horizontal displacements

An extrapolation of the correction factor, $c(M_o - M_{calc})$, into the range of M_{calc} values observed for Long Shot yields a value of +0.3 to +0.4. Applying this correction makes the vertically determined Ms greater than the horizontally determined value. As the avowed purpose of this correction is to equalize the magnitude determinations, $c(M_o - M_{calc})$ was chosen to be zero.

With the assumption of zero amplitude for the unobserved horizontal component, the average value of Ms from the horizontal components is 4.2. With the assumption of a zero correction factor in the vertical determination, the average value of Ms is 4.1.

An empirical relationship between Ms and body wave magnitude, m_b, has been formulated by Gutenberg and Richter (1956):

$$m_b = 0.63 \text{ Ms} + 2.5$$

Applying this relationship, an average value of m_b = 5.1 is obtained from the surface waves as opposed to an average value of m_b = 6.0 from the P wave magnitude determination.

A plot of the calculated value of Ms versus the corresponding value of m_b from P waves (Fig. 13) shows that none of the Long Shot data satisfies the suggested relationship. This is to be

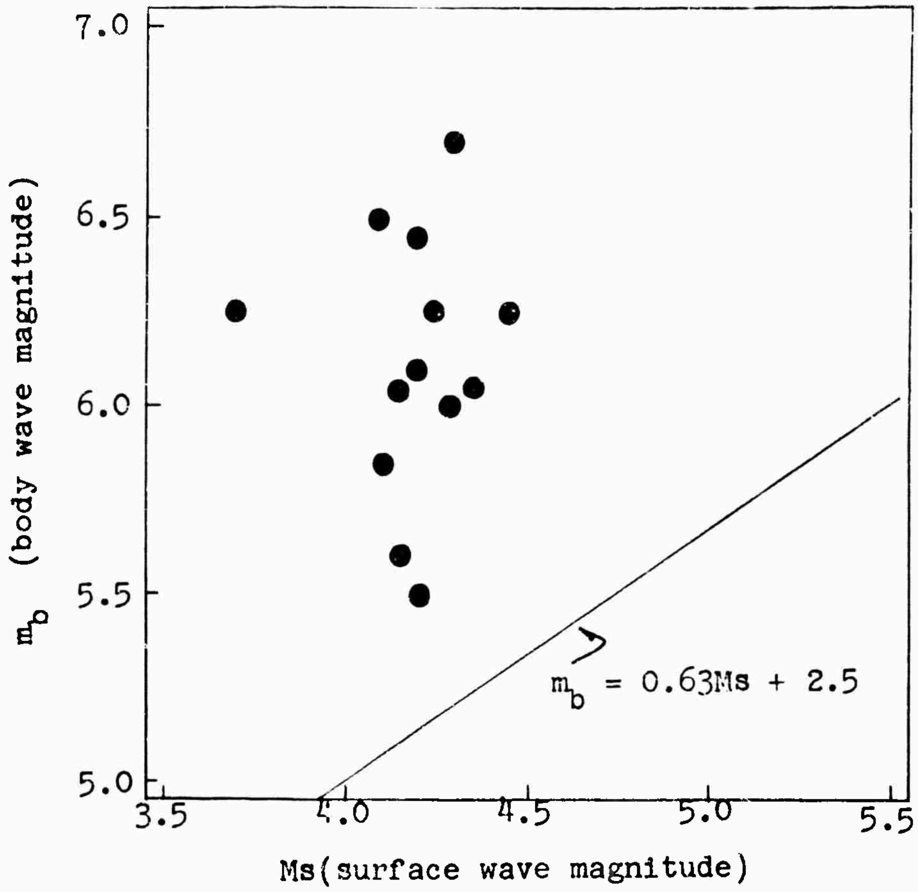


FIG. 13. Long Shot body wave magnitude versus surface wave magnitude a Canadian stations. curve (m_b = 0.63Ms + 2.5) from Gutenberg and Richter (1956). Body wave magnitudes from Jensen et al (1966).

contrasted with the results of Gutenberg and Richter (1956) who found little indication of systematic deviation from the axis of zero residual from seismic waves of earthquake origin. However, they also noted that the proportion of the energy transferred to surface waves decreased rapidly as the magnitude of the earthquake decreases. They attributed this effect to a reduction in the linear dimensions of the source, an explanation which, if correct, is clearly applicable to the restricted volume, impulsive model of an explosive source.

CHAPTER III

TIME RESIDUALS

3-1 Introduction

To study travel time residuals, regional variations in crustal velocities must be known. In the United States, the mean P wave crustal velocities may be summarized on a regional basis as follows (Pakiser and Zietz, 1965):

(1) western orogenic belts - less than 6.2 km/sec to 6.5 km/sec

(2) coastal plains - less than 6.2 km/sec

(3) Appalachian orogenic belts - 6.2 km/sec to 6.5 km/sec

(4) shield and central stable region - greater than 6.5 km/sec

Assuming an average crustal thickness, velocity differences in the crust alone can explain, at most, a 0.6 sec difference in arrival times. However, the Pn velocities exhibit a similar trend of higher and lower than average values. Further, Cleary and Hales (1966) have found travel time residuals which are related in a similar way to the tectonic history of the region. This implies that the near-surface pattern extends some depth into the mantle.

In addition to the residuals resulting from the regional velocity variations, there is a contribution to the total travel time residual from inaccuracies in the Jeffreys-Bullen travel time tables (Chinnery and Toksöz, 1967).

3-2 Long Shot Travel Time Residuals

The Jeffreys-Bullen P wave travel time residuals observed at the Canadian and LRSM seismic networks in North America are shown in Figs. 14 and 15 (see also Tables 9 and 10). The large,

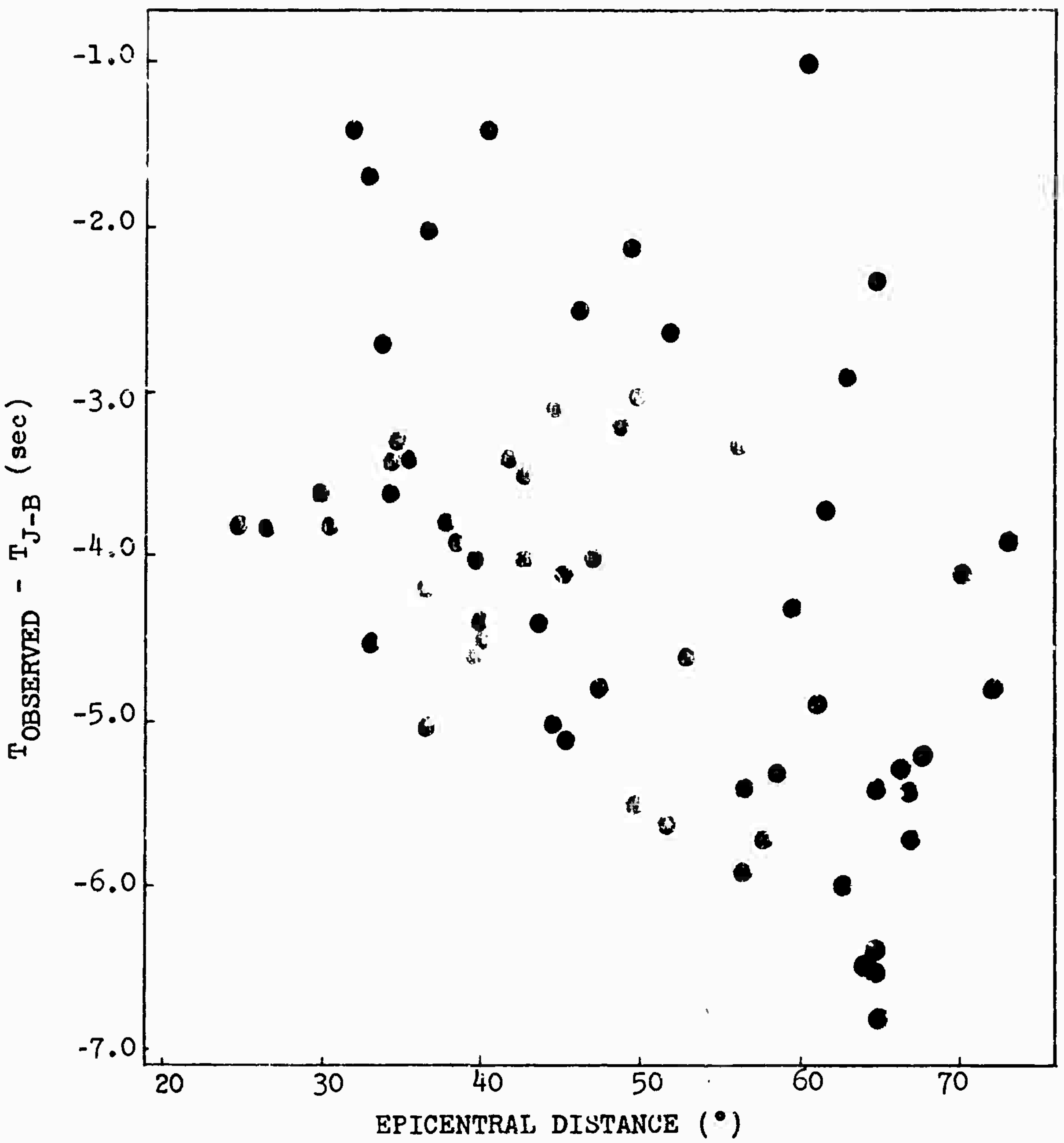


FIG. 14. Long Shot travel time residuals at North American stations as a function of epicentral distances. Values used are listed in Tables 9 and 10.

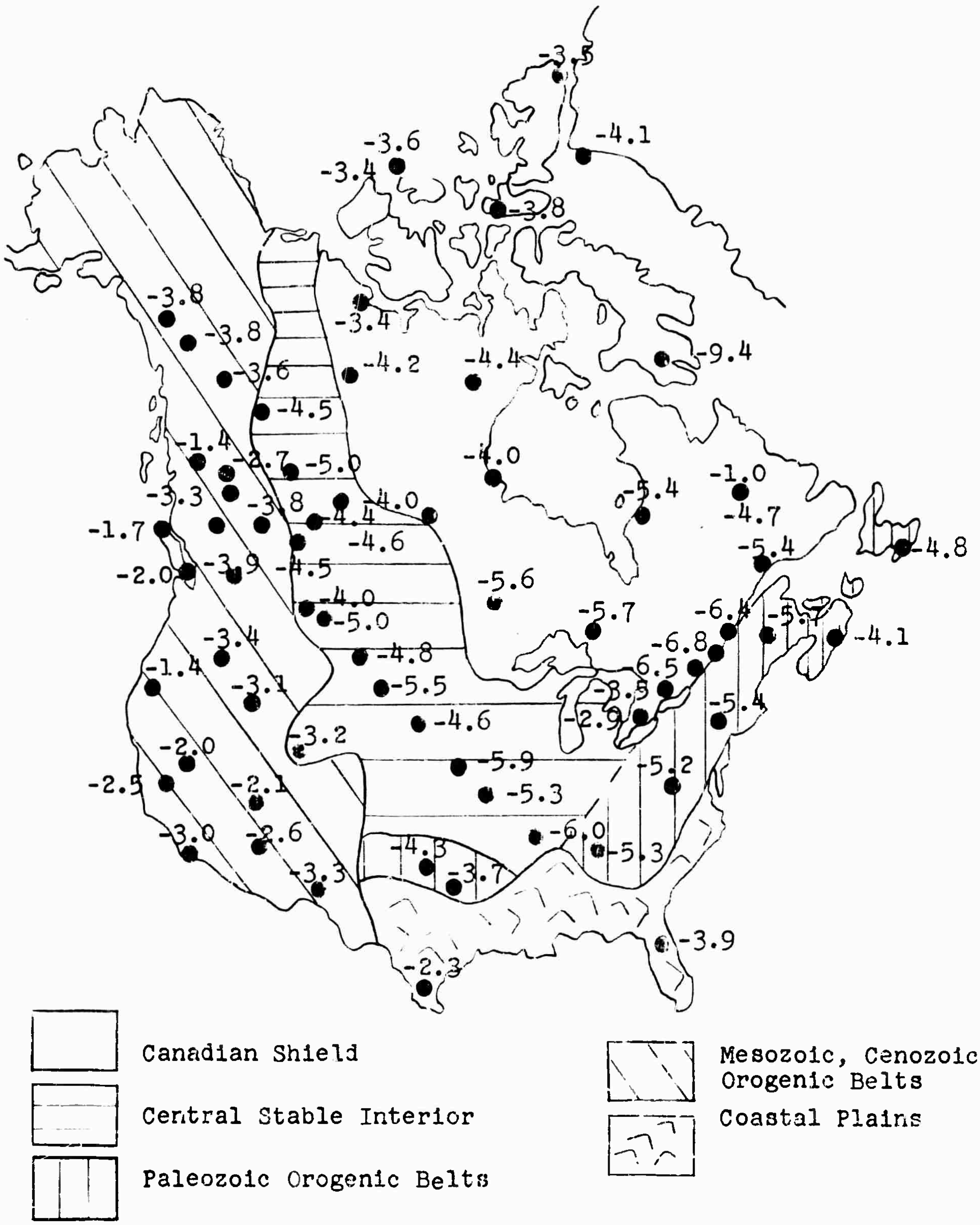


FIG. 15. Long Shot travel time residuals and the major tectonic divisions of North America.

Table 9

Long Shot Jeffreys-Bullen Time Residuals
at
LRSM Stations*

	STATION	J-B (sec) Residual		STATION	J-B (sec) Residual
BH-YK	Burwash Landing	-3.8	KN-UT	Kanab	-2.1
WH-YK	Whitehorse	-3.8	RG-SD	Redig	-5.5
WL-YK	Watson Lake	-3.6	CP-CL	Campo	-3.0
SI-BC	Smithers	-1.4	RK-ON	Red Lake	-5.6
FL-BC	Fort Nelson	-4.5	TFSO	Tonto Forest Obs.	-2.6
NP-NT	Mould Bay	-3.6	WN-SD	Winner	-4.6
PG-BC	Prince George	-3.3	LC-NM	Las Cruces	-3.3
KV-AT	Keg River	-5.0	CR-NB	Crete	-5.9
JP-AT	Jasper	-3.8	KC-MO	Kansas City	-5.3
WS-AT	Waterways	-4.0	WMSO	Wichita Mt. Obs.	-4.3
YR-CL	Yreka	-1.4	SV3QB	Schefferville	-1.0
BMSO	Blue Mt. Obs.	-3.4	GV-TX	Grapevine	-3.7
SW-MA	Sweetgrass	-4.0	EN-MO	Ellsinore	-6.0
HLZID	Hailey	-3.1	SJ-TX	San Jose	-2.3
HV-MA	Havre	-5.0	CDSO	Cumberland Plat.	-5.3
MN-NV	Mina	-2.0	DH-NY	Delhi	-5.4
TE-GL	Thule	-4.1	HN-ME	Houlton	-5.7
TF-CL	Taft	-2.5	FN-WV	Franklin	-5.2
CH-MT	Fort Churchill	-4.0	BE-FL	Belleview	-3.9
LAO	LASA, D3-10	-4.8			
VBSO	Vinta Basin Obs.	-3.2			

* arrival times from Clark (1965)

Table 10

Long Shot Jeffreys-Bullen Time Residuals
at
Canadian Stations*

	STATION	J-B (sec) Residual		STATION	J-B (sec) Residual
ALE	Alert	-3.5	PHC	Port Hardy	-1.7
BLC	Baker Lake	-4.4	RES	Resolute	-3.8
CMS	Coppermine	-3.4	STJ	St. Johns	-4.8
EDM	Edmonton	-4.4	SCB	Scarborough	-3.5
FFC	Flin Flon	-5.1	SCH	Schefferville	-4.9
FSJ	Fort St. James	-2.7	SIC	Sept Iles	-5.4
FBC	Frobisher	-9.4	SFA	Seven Falls	-6.4
GWC	Great Whale	-5.4	SHF	Shawinigan Falls	-6.5
HAL	Halifax	-4.1	VIC	Victoria	-2.0
LNP	London	-2.9	YKC	Yellowknife	-4.2
MNT	Montreal	-6.8	LD6	Leduc	-4.6
MBC	Mould Bay	-3.4	RM6	Rocky Mt. House	-4.5
OTT	Ottawa	-6.5	WAW	Wawa	-5.7
PNT	Penticton	-3.9			

* arrival times from Jensen et al (1966).

consistently negative residuals indicate a peculiarly high velocity upper mantle in the region of the Aleutian Arc (Chinnery and Toksöz, 1967).

The average residual was -3.5 sec which may be considered to a first approximation to be the bias introduced near the source by an anomalous crust and upper mantle. On this basis, time residuals less than -3.5 sec indicate a relatively late arrival while time residuals greater than -3.5 sec indicate a relatively early arrival. Using this rather arbitrary division, the observed time residuals may be examined for regional trends and variations.

Despite the scatter which is inherent in the readings, correlations are indicated with the major tectonic divisions of North America (after Eardley, 1962). Arrivals in the recent orogenic belts of western North America (average time residual -2.7 sec) and in the coastal plains (average time residual -3.1 sec) tend to be relatively late. Arrivals in the shield (average time residual -5.1 sec), central stable region (average time residual -4.4 sec) and the older Paleozoic orogenic belts of the eastern and southern United States (average time residual -4.4 sec) tend to be relatively early. Although the arrivals in the Paleozoic orogenic belts would, on the basis of mean crustal velocities, be expected to be later than arrivals in the central stable region, this effect appears to be obscured by the strong tendency of the residuals to increase with distance. The arrivals tend to be earliest in the shield area as would be expected.

As has been mentioned, the Pn and mean crustal velocities tend to vary in the same way. High Pn and mean crustal velocities

tend to be associated, as do low Pn and mean crustal velocities. When the cumulative effect of these velocities is considered, it becomes feasible to explain a large part of the time residuals in terms of velocity variations near the station and from station to station. After correcting the arrival times for the effect of different mean crustal velocities at the stations, a further adjustment is made by assuming that the Pn velocity contrast continues to depth. This calculation ignores the fact that the true velocity contrast must tend to zero with depth but it should be a reasonable first approximation. Applying this method to the difference in time residuals between Havre (HV) in the central stable region and Kanab (KN) in the western orogenic belt, a depth of about 200 km is indicated below which the mantle is uniform, a not unreasonable depth.

This technique is also useful in pointing out inconsistencies in crustal models. The Long Shot travel time residuals indicate that the velocities under PNT are higher than under FSJ whereas the opposite trend has been suggested as the most suitable on the basis of the limited refraction data available. In the next section, earthquake travel time residuals are examined at FSJ and PNT in an attempt to ascertain the most feasible velocity distributions beneath these stations.

The final factor that may contribute to the observed Long Shot travel time residuals is inherent errors in the Jeffreys-Bullen travel times. Chinnery and Toksöz (1967) have shown that their modified velocity-depth model of the mantle already discussed will explain part of the variation in Long Shot residuals after

local corrections have been applied. This model will account for, at most, a 2.5 sec difference in residuals as compared with a maximum observed difference of approximately 8.0 sec. This further emphasizes the importance of local factors in determining travel time residuals.

3-3 Penticton and Fort St. James Travel Time Residuals

Earthquake travel time residuals were calculated at Penticton and Fort St. James for comparison with the values obtained from Long Shot. The residuals obtained were also examined for correlations with the source parameters to determine the extent of the regional bias of events in the Aleutian Arc region.

The usefulness of travel time residuals depends on an accurate knowledge of epicenter location, depth, origin time, station location, timing accuracy an unambiguous first arrivals.

In this study, the epicenter locations, depths and origin times published by the U.S.C.G.S. were used. They give standard errors in both latitude and longitude that typically range from ± 5 to ± 40 km. In cases where the depth is not constrained, the standard error in depth typically ranges from ± 10 to ± 50 km. Depths are constrained (or in U.S.C.G.S. terminology "restrained") if they are well established by pP arrivals or if they become negative at any time during the computation in which case they are set at 33 km. The standard errors in origin time are typically ± 1.0 sec or less. Although these standard errors give a measure of the constancy of the data rather than probable error in the computation, they may be considered as a measure of the accuracy

with which the source parameters are known.

Station locations are known to the nearest minute of arc.

Epicentral distances were calculated with a correction for the eccentricity of the earth.

Time at FSJ and PNT is provided by chronometers which are checked against a national standard at the beginning and end of each record. Although the accuracy of the time varies, it does not seem to do so in a systematic manner so that the errors introduced by this source should have a negligible effect on the means of the large samples considered.

To minimize arrival time ambiguity, only data from well defined, impulsive arrivals has been used. These arrivals can be read to ±0.1 sec.

Theoretical travel times were calculated from interpolated Jeffreys-Bullen Seismological Tables (Travis, 1965) in which the travel times are given to the nearest 0.1 sec at one degree intervals at each of the fourteen standard focal depths. The Lagrangian four-point interpolation polynomial was used to interpolate between the degree intervals and linear interpolation was used to interpolate between the standard depths.

The final criterion applied was that the magnitude of the time residual be less than 5.0 sec. This is suggested by Tryggvason (1964) who noted that his time residual data were normally distributed when this constraint was applied. Although there is no a priori reason why time residuals should be normally distributed, large residuals are much more likely to be due to

accidental errors such as misinterpretation of phases or clerical errors.

The application of the above criteria to the PNT and FSJ data for the February 1965 to August 1966 period produced 204 suitable arrivals at PNT and 64 at FSJ (Table 11). Although the sample sizes differ considerably, the means and standard deviations of the depths, magnitudes, azimuths and epicentral distances indicate that they were drawn from substantially the same populations.

To determine confidence limits on the mean values of the time residuals it is necessary to know the distribution function which the data satisfy. The histograms of the data showed substantial departures from a normal distribution for time residuals larger than 2.75 sec. An examination of the scatter plots of the time residuals versus distance and versus depth showed that the large residuals were all associated with near events ($< 30°$) or deep events (> 200 km). Travel times from near events are known to be strongly affected by regional variations in crust and upper mantle structure. Cleary and Hales (1965) recommend that the sample be restricted to shallow events to avoid possible complications due to large variations in focal depth. For these reasons, data from near or deep events were eliminated from the sample (Table 12).

The histograms of the data (Figs. 16 and 17) and fitted normal curves show that the data is substantially normally distributed. The mean time residuals are 0.17 ± 0.13 sec at PNT and 0.54 ± 0.26 sec at FSJ for 95 per cent confidence limits.

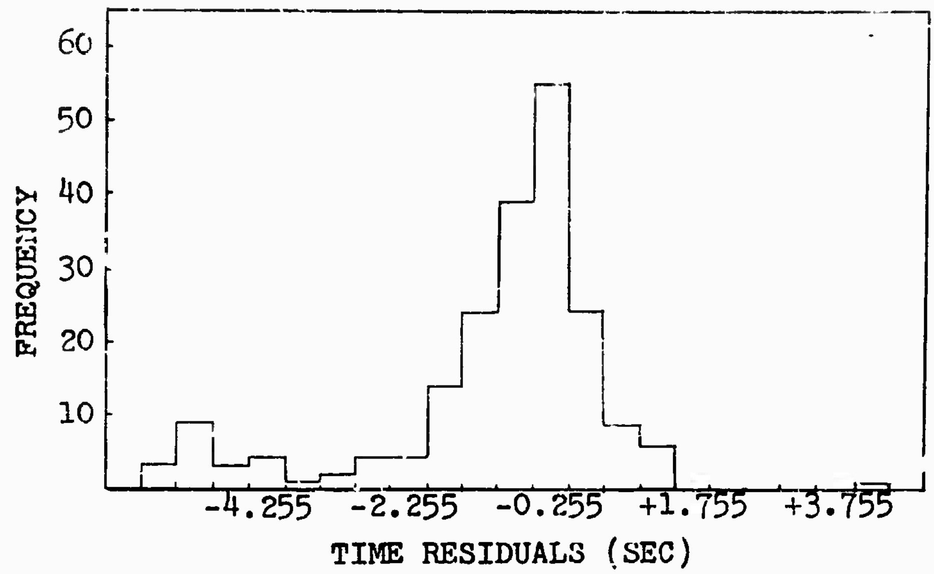


FIG. 16. Histogram of earthquake travel time residuals at Penticton

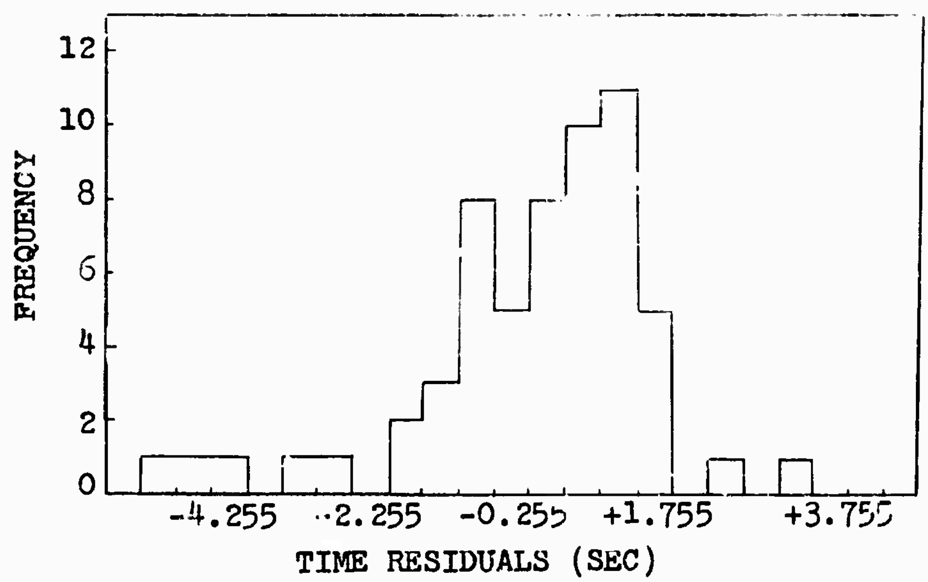


FIG. 17. Histogram of earthquake travel time residuals at Fort St. James.

Table 11 Original Sample(Time Residuals)

	PNT (204 values) mean	PNT st. dev.	FSJ (64 values) mean	FSJ st. dev.
depth (km)	95.93	124.59	92.05	121.29
magnitude	5.45	0.52	5.84	0.42
distance °	61.32	22.69	61.53	22.43
azimuth °	239.06	77.94	265.32	97.87
residual (sec)	- 0.26	1.61	0.26	1.73

Table 12 Modified Sample (Time Residuals)

	PNT (182 values) mean	PNT st. dev.	FSJ (57 values) mean	FSJ st. dev.
depth (km)	67.86	62.63	64.75	57.80
magnitude	5.45	0.50	5.86	0.40
distance °	60.17	22.26	61.28	22.44
azimuth °	273.06	79.59	252.43	100.12
residual (sec)	0.17	0.86	0.54	1.02

Table 13 Common Source Time Residuals

	PNT (24 values) mean	PNT st. dev.	FSJ (24 values) mean	FSJ st. dev.
depth (km)	53.17	44.86	53.17	44.86
magnitude	5.98	0.43	5.98	0.43
distance °	57.73	21.23	55.89	23.16
azimuth °	244.81	93.23	238.98	91.66
residual (sec)	0.00	0.75	0.67	0.98

It is possible that a bias is introduced by comparing residuals from what are, in fact, different samples. If the sample is restricted to common source events (Table 13), time residuals of 0.00 ± 0.32 and 0.67 ± 0.42 seconds are obtained for PNT and FSJ respectively for 95 per cent confidence limits. These values are in agreement with the mean time residuals given above although the sources tend to be of larger average magnitude and closer as would be expected. The PNT arrivals are consistently early with respect to the FSJ arrivals.

As the crustal and upper mantle velocities are more accurately known at PNT than FSJ, this indicates that the mean crustal velocity at FSJ is less than 6.0 km/sec as opposed to the 6.1 km/sec suggested earlier and that the Pn velocity is probably less than 7.8 km/sec rather than 8.0 or 8.5 km/sec as already suggested. Both the mean crustal and Pn velocity at FSJ must be less than at PNT to explain the observed time residuals in terms of variations in crustal and upper mantle velocities.

3-4 Comparison of Long Shot and Earthquake Time Residuals

As has been indicated, the Penticton and Fort St. James stations were chosen for study because the Long Shot records suggested that they represented different regimes. This has been partially confirmed by the earthquake magnitude residuals and due to the correlation between tectonic environment, magnitude and time residuals already discussed, the time residuals should also reflect this difference.

Although the observed Long Shot time residuals should

not depend on the nature of the source, other than to be more accurate because of precise knowledge of location and origin time, they should reflect its geographical and geological location. For this reason, the Long Shot time residuals are compared with those of earthquakes with similar source parameters to determine whether or not they may be considered representative of the Aleutian Arc region (Table 14).

Table 14

Earthquake and Long Shot Travel Time Residuals at PNT and FSJ

Sample	PNT sec	FSJ sec	PNT-FSJ sec
Long Shot	-3.9	-2.7	-1.2
Earthquakes			
depth 0-20 km	- .46	.55	-1.01
distance 34-42°	.46		
30-38°		1.29	- .83
azimuth 292-302°	.30		
284-294°		1.54	-1.24
distance and azimuth of Long Shot	.47	1.13	-0.66
all values	- .26	.26	- .52
modified sample	.17	.54	- .37
common source	0.00	.67	- .67

In the cases considered, the PNT arrivals are consistently early with respect to the FSJ arrivals. As has been mentioned, this must reflect dif[illegible] velocity distributions beneath the stations. The mean earthquake travel time residuals are most

simiiar to the Long Shot values at these stations for shallow events and events from the same azimuthal zone as Long Shot.

The comparison is, however, limited by uncertainties in earthquake travel time residuals and by the fact that mean residuals are being compared with a single set of readings. Using two times the standard deviation as a measure of the scatter of the data, a range of differences of -0.67 ± 1.70 sec is obtained, from common events, between these stations. As the difference of -1.2 sec obtained from Long Shot at these stations falls well within this range, the difference in residuals must be considered representative of events in the Aleutian region.

Although the magnitude of the difference in travel time residuals obtained from earthquakes is comparable to that from Long Shot, the consistently negative travel time residuals exhibited by Long Shot were not observed. This effect, if present, is probably obscured by considering mean values and the errors in earthquake travel time residuals.

3-5 Functional Relationships

The time residuals were also examined for functional relationships with depth, epicentral distance and azimuth.

A strong correlation with depth was indicated with linear correlation coefficients of -0.67 and -0.77 for PNT and FSJ respectively. This was due to the concentration of large, negative time residuals with deep events.

The time residuals showed a roughly sinusoidal variation with distance. Peaks were indicated at approximately 40 and 85° with a trough at approximately 60°. This is consistent with the

travel time residual versus distance curves given by Carder (1964), Cleary and Hales (1965) and Chinnery and Toksöz (1967).

Although the azimuthal distribution of data was poor, the arrivals from the first and second quadrants tended to be late relative to arrivals from the third and fourth quadrants.

CHAPTER IV

SPECTRAL ANALYSIS OF EARTHQUAKE AND LONG SHOT DATA

4-1 Introduction

The spectrum of a seismic signal is determined by the source, travel path and seismometer characteristics. The seismometer characteristics can be removed so that remaining station to station variations result from transmission path differences and the radiation pattern of the source. Assuming the explosive source is symmetric station to station variations in the spectra from an explosion should reflect transmission path differences.

Amplitude spectra may be compared in terms of their attenuation rates by fitting to the spectrum a function

$$B(f) = D\exp(-\gamma f) \qquad (1)$$

where: $B(f)$ = amplitude as a function of frequency

D = constant

$-\gamma$ = slope of the logarithm of the amplitude spectrum

For a plane wave, amplitude as a function of distance and frequency is proportional to

$$\exp(-\alpha x) \qquad (2)$$

where

$$\alpha = \frac{\pi f}{CQ}$$

and α is the spatial attenuation factor, x is distance, C is phase velocity and $1/Q$ is the specific attenuation factor. The specific attenuation factor describes the contribution of anelasticity to the loss of amplitude and is defined as

$$\frac{1}{Q} = \frac{\Delta E}{E}$$

where ΔE is the energy dissipated per cycle and E is the peak elastic

energy for that period. Gutenberg (1958) has suggested that $Q \approx 400$ for P wave amplitudes.

From (1) and (2) it can be seen that for a homogeneous earth

$$\frac{\pi X}{CQ} = \gamma$$

if the source function is assumed to be constant. An order of magnitude calculation indicates that γ should be about 2 or 3 at 35°. Clearly, γ would be expected to increase with distance, all other factors being equal. However, for a more realistic model of the earth both Q and C will vary for different transmission paths and along each transmission path. Other possibilities, such as Q being a function of frequency, should also be considered. For these reasons it is not possible to directly relate γ to either spatial or specific attenuation factors but only to consider it as a measure of attenuation at a particular station of a particular event.

In this case, the power spectra will be considered as a function of frequency

$$P(f) = C \exp(-\beta f)$$

where β is the spectral decrement and

$$\beta \approx \frac{2\pi X}{CQ}$$

The variations in spectral decrement will reflect differences in path length and source spectra as well as changes in the transmission properties of the material through which the seismic wave propogates.

Jensen et al (1966) present power and amplitude spectra of the vertical component of the Long Shot arrival at a number of Canadian stations. They noted that the spectral decrement was significantly greater at Victoria and Wawa than at Leduc and Rocky

Mt. House. Victoria, Rocky Mt. House and Leduc were at a distance of 36.1, 39.2 and 39.7° respectively from Long Shot with station to source azimuths of 299.9, 295.8 and 295.7° so that the travel paths in the vicinity of the source should have been practically identical. The paths would be different in the mantle and, of course, in the vicinity of the stations. As the deeper mantle is thought to be homogeneous, it seems probable that a large part of the station to station variation in Long Shot spectra noted by Jensen et al (1966, can be attributed to the crust and upper mantle in the vicinity of the stations. Ichikawa and Basham (1965) have stressed the importance of the crust and upper mantle in determining variations in spectral decrement between stations.

Intuitively, it would be expected that an explosion might yield higher frequencies than earthquakes because of its impulsive nature and restricted volume relative to an earthquake source. That is, the spectral decrement of the Long Shot signal should be smaller than that of earthquakes unless the source effect is obscured by local crustal and upper mantle structure. Hence a comparison of earthquake and Long Shot spectra may indicate characteristics that could be useful to identify the source mechanism as well as the relative importance of the various effects that determine the slope of the observed spectra. For these reasons, the Long Shot spectra at Leduc, Rocky Mt. House and Victoria are compared with earthquake spectra.

Finally, if variations in the Long Shot spectral decrement are largely determined by the crust and upper mantle in the vicinity of the stations, they may delineate the anomalous region in central

British Columbia and the southern Yukon. Therefore, the Long Shot spectra at stations within this region are calculated and compared with Long Shot spectra from other stations.

4-2 A Comparison of Long Shot and Earthquake Spectra

The Long Shot spectra at Leduc and Rocky Mt. House can be compared with the spectra of earthquakes recorded at these stations by the Arctic Institute of North America (under Grant AF-AFOSR-702-64) during the summer of 1965. The power spectra of the first 20 sec of the vertical component of the P wave arrivals have been provided by R. M. Ellis and P. W. Basham.

Figs. 18 and 19 show the Long Shot spectra at Leduc and Rocky Mt. House as well as the spectra of an earthquake (October 27, 1965; location: 51.9° N, 175.5° E; depth: 41 km; magnitude: 5.5 - USCGS determination) with source parameters comparable to Long Shot. The averaged earthquake spectra at Leduc and Rocky Mt. House are also shown.

The spectra of both the earthquake and Long Shot at Rocky Mt. House are quite featureless and fall off rapidly with frequency whereas the spectra of the same events recorded at Leduc have well defined peaks and troughs and fall off relatively slowly. As the sources are common and the stations are not widely separated geographically, this is likely due to a modification of the signal by the crust and upper mantle in the vicinity of the stations.

The spectra (Figs. 18 and 19) may be compared in terms of spectral decrement which is one measure of the energy distribution in the signal. Given a common source and approximately equidistant stations, any variation in spectral decrement between

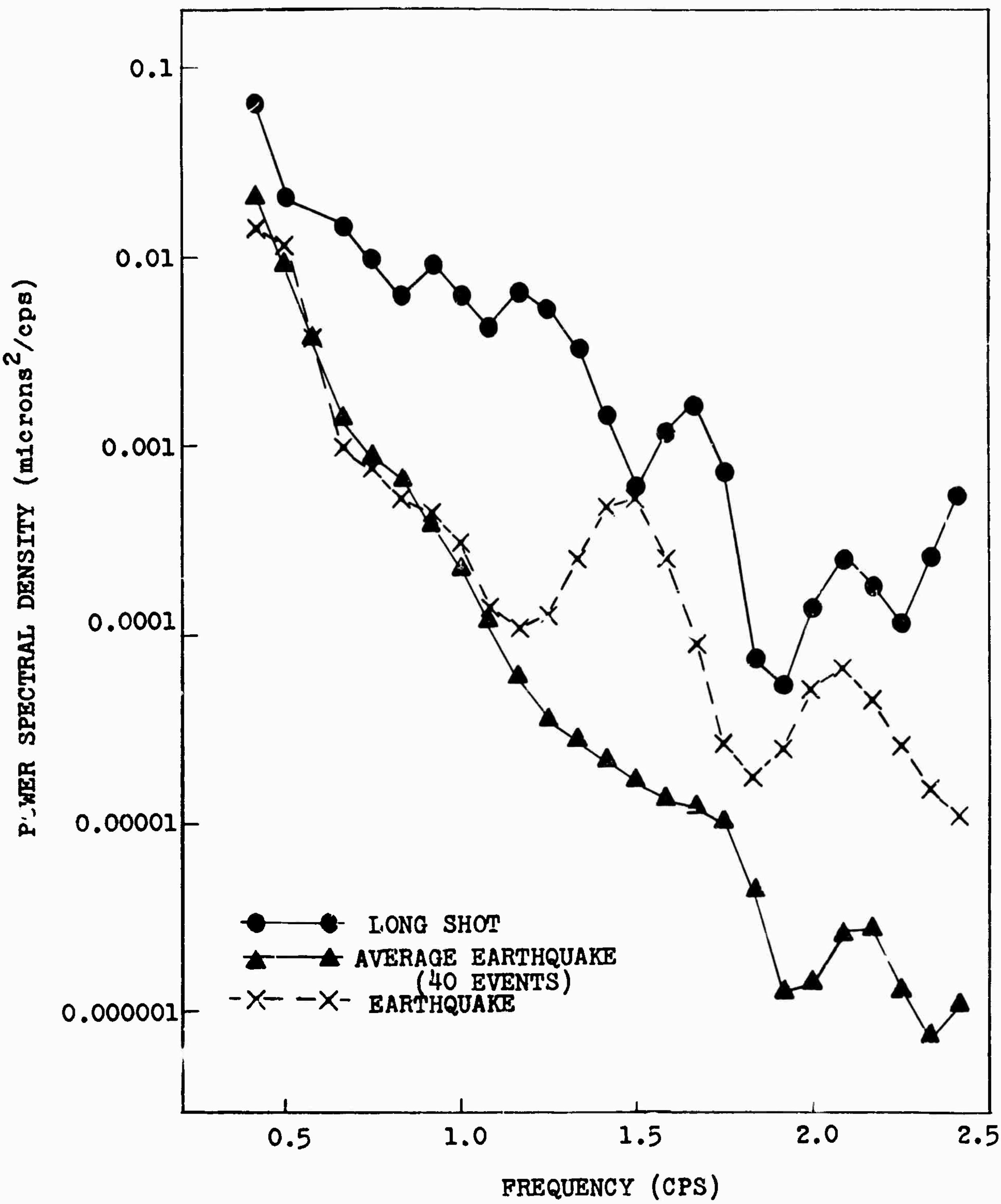


FIGURE 18. Spectra of Long Shot and earthquakes at Leduc.

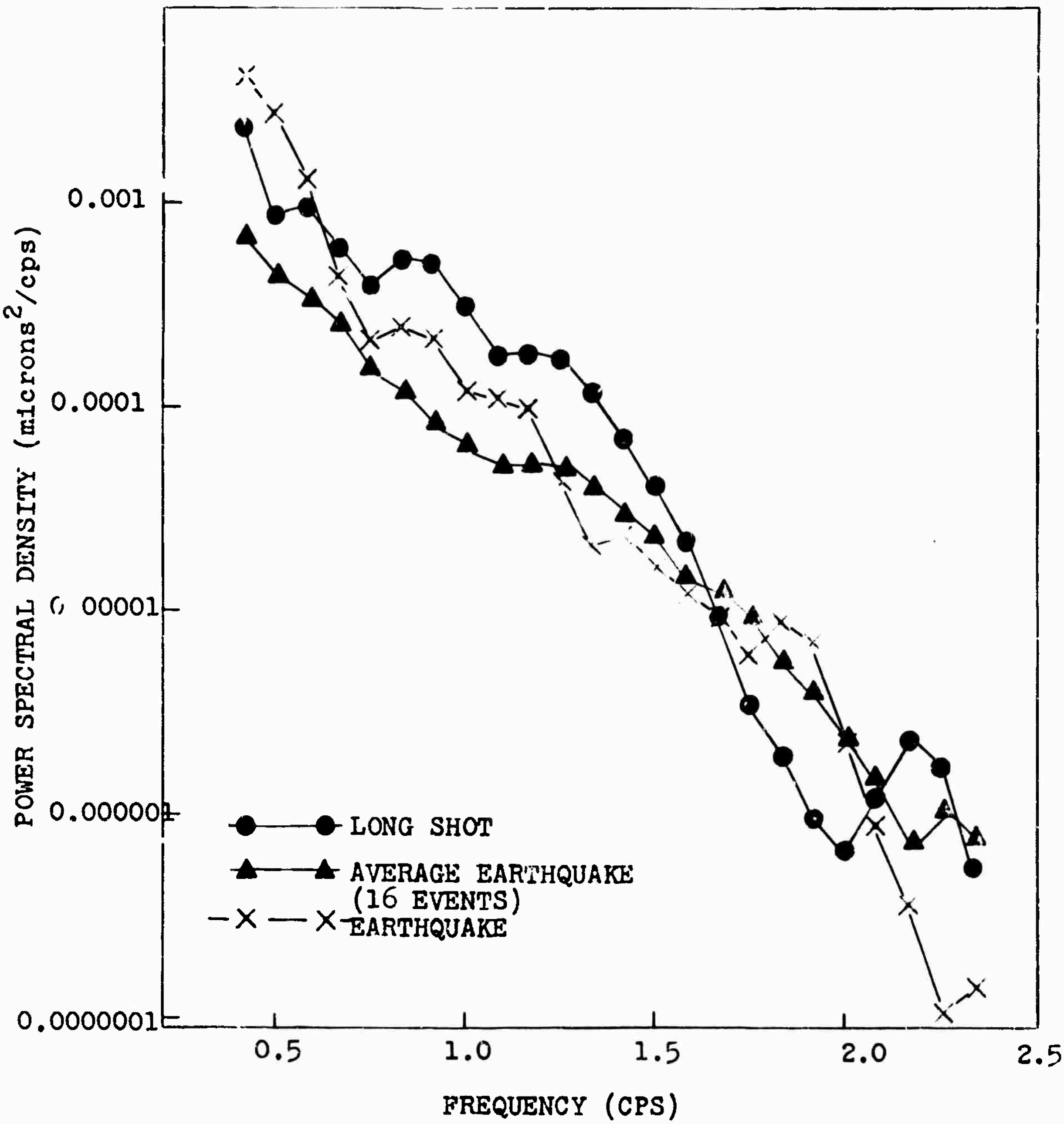


FIGURE 19. Spectra of Long Shot and earthquakes at Rocky Mt. House.

stations should be due to attenuation or reverberation in the crust and upper mantle in the vicinity of the station. The spectral decrements are 4.4 ± 0.8 and 6.0 ± 1.5 sec/cycle at Leduc and 7.2 ± 1.4 and 7.4 ± 1.3 sec/cycle at Rocky Mt. House for Long Shot and the earthquake.

Both visual inspection of the spectra and spectral decrements indicate relatively more energy at higher frequencies in the Long Shot signal than in the earthquake generated signal with otherwise comparable source parameters.

However, this comparison has been between a single earthquake and Long Shot and it is important to determine whether or not this is generally true. The average spectral decrement of the earthquakes grouped by azimuthal, distance and depth zones as well as the spectral decrement of Long Shot at Leduc and Rocky Mt. House are shown in Table 15.

Table 15.

Spectral Decrements at Rocky Mt. House and Leduc

Source	No.	β sec/cycle	95% conf. lts.	No.	β sec/cycle	95% conf. lts.
Long Shot	1	7.2	± 1.3	1	4.4	± 0.8
Earthquakes average	16	7.1	± 1.0	40	7.2	± 1.4
$\Delta \approx 40°$	5	7.3	± 1.3	13	6.9	± 1.3
$\Delta > 50°$	4	6.5	± 0.9	15	7.0	± 1.3
$\Delta < 30°$	6	7.3	± 1.2	11	7.0	± 1.0
az $\approx 295°$	3	7.0	± 1.1	22	6.8	± 1.2
az $\approx 140°$	4	6.6	± 1.0	7	6.5	± 1.1
depth < 33 km	10	7.2	± 1.1	24	7.3	± 1.3
depth > 33 km	6	6.8	± 1.2	15	6.5	± 1.1
common sources	16	7.1	± 1.0	16	6.6	± 1.1

The average spectral decrement of the earthquakes recorded at Rocky Mt. House is 7.1 ± 1.0 sec/cycle versus 7.2 ± 1.3 sec/cycle for Long Shot. These values are indistinguishable due to the wide 95 per cent confidence limits. The difference at Leduc is more significant with an average earthquake spectral decrement of 7.2 ± 1.4 sec/cycle versus 4.4 ± 0.8 sec/cycle for Long Shot. Only one of the 40 events recorded at Leduc (azimuth: 138.1°; distance: 81.4°; depth: 129 km; magnitude: 6.0; spectral decrement: 4.6 ± 0.8 sec/cycle) had a spectral decrement comparable to that obtained for Long Shot, all others were at least one unit larger. This suggests that the difference in spectral decrements is partly due to different source mechanisms and as such, may have application to the problem of distinguishing explosive from natural seismic sources at the Leduc station at least.

The very large difference in spectral decrements between Long Shot at Leduc and Rocky Mt. House is difficult to reconcile with the idealized, symmetric model of an explosive source. As the spectral decrement of Long Shot at Leduc is near the average for the stations recording Long Shot considered (see Tables 15, 17 and 18) the observation that requires explanation is the large spectral decrement of Long Shot at Rocky Mt. House.

A more detailed examination of Table 15 does not indicate significant correlations with any of the source parameters with the exception of a weak tendency for the sample to be less than the mean if it is restricted to events with epicenters at depths greater than 33 km or events in the 140° azimuthal zone. There is also a weak tendency for the spectral decrement to increase with

increased distance to source which is obscured by the averages given in Table 15.

Earthquake data was also obtained from a magnetic tape recording seismograph operated in the Victoria vault for one week. During this period, 3 suitable events were recorded (Table 16).

Table 16

Earthquakes Recorded at Victoria

Date*	Region	Lat.	Long.	Depth km	Mag	Distance °	Azimuth °
May 18, 1966	Gulf of Calif.	25.0N	109.0 W	normal	5.3	25.7	149.1
May 19, 1966	Unimak Is.	54.1N	164.1 W	28	5.8	26.0	298.6
May 20, 1966	Vanc. Is.	50.2N	129.66W	37	5.0	4.7	298.3

*U.S.C.G.S. determinations

The power spectra of the first minute of the vertical component of the signal are shown in Fig. 20 and the calculated spectral decrements in Table 17.

Table 17

Spectral Decrements at Victoria

source	spectral decrement, β (sec/cycle)	95% confidence limits
Long Shot	4.3	±1.0
Gulf of Calif.	5.9	±1.0
Unimak Is.	6.9	± .6
Vanc. Is.	3.8	± .6

Although the spectral decrement of Long Shot at Victoria was thought (Jensen et al, (1966)) to be anomalously large with

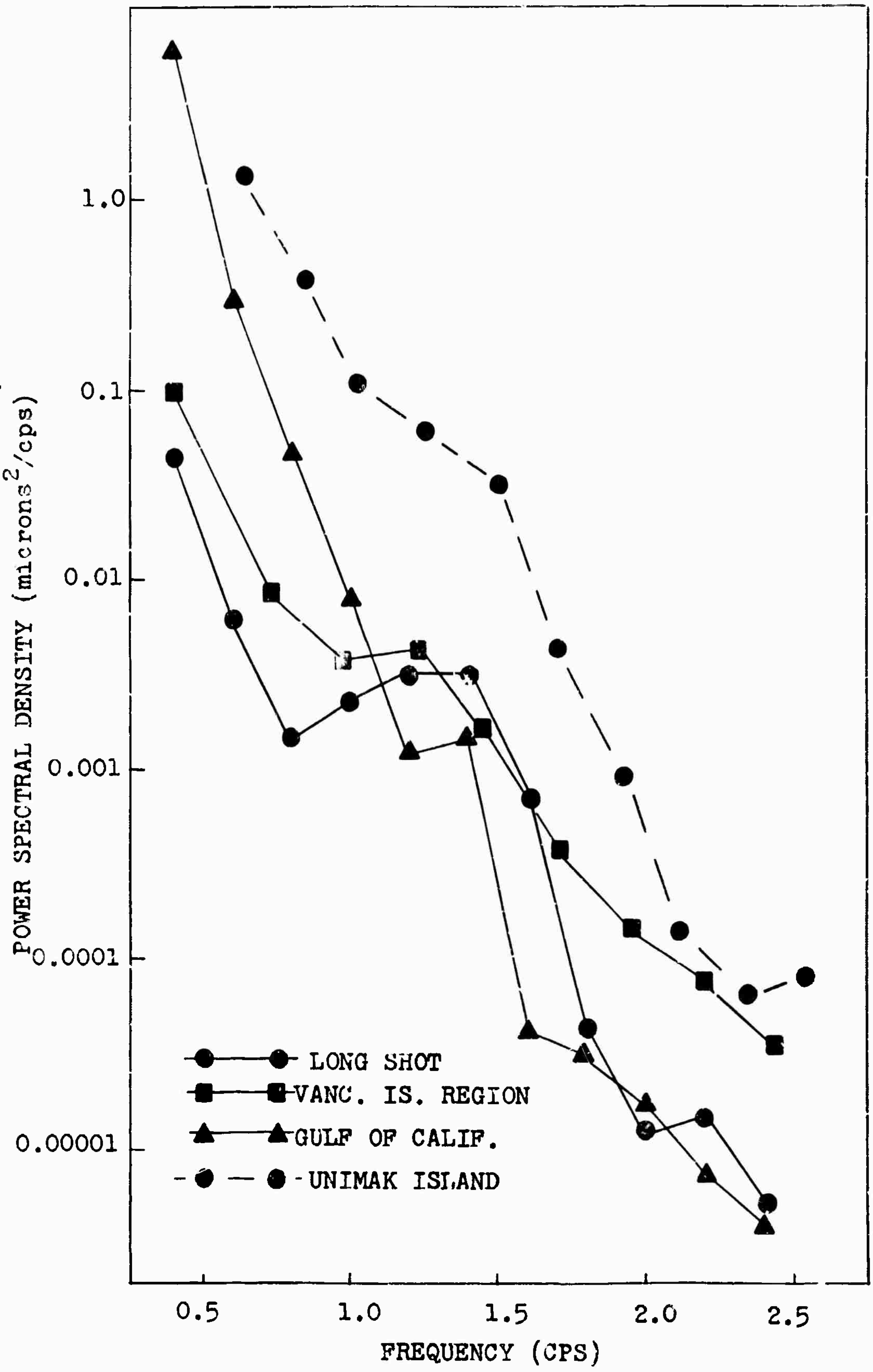


FIGURE 20. Long Shot and earthquake spectra at Victoria.

respect to Leduc and Rocky Mt. House, this comparison indicates that it is comparable to the spectral decrement at Leduc (see Table 15) and that it is the spectral decrement of Long Shot at Rocky Mt. House that is anomalously large. Further, the spectral decrements of the Gulf of California (5.9 sec/cycle) and Unimak Island (6.6 sec/cycle) events are large than that of Long Shot (4.3 sec/cycle) at this station.

The Vancouver Island event cannot be legitimately compared with the teleseismic events as it was only 4.7° from the station. At this distance the first minute of signal would contain phases other than P. Despite this, its spectral decrement is of interest as it is markedly smaller (3.8) than the spectral decrements of the other events. This is probably a distance-from-source effect as spectral decrement is proportional to distance and this event was only 4.7° from Victoria as opposed to 36.0° from the source of Long Shot to Victoria.

At Leduc and Victoria the spectral decrement of Long Shot was smaller than the average spectral decrement of the earthquakes at comparable distances which is probably due to the differences in source mechanisms. The spectrum of Long Shot at Rocky Mt. house appeared to be anomalous in that its spectral decrement was larger than that of Long Shot at the other stations and, on the average, indistinguishable from the spectra of the earthquakes recorded at the station. This may be partially due to the high level of the low frequency noise at Rocky Mt. House.

Despite these differences in spectral decrements, the character of the spectra from the two types of sources was similar at each station which suggests that it is partially

determined by local factors.

There was also a tendency for the spectral decrement to increase with increased distance to source as it should from theoretical considerations.

4-3 Long Shot Spectra at Western Canadian and American Stations

The spectra of the Long Shot arrivals in and around the anomalous region of central British Columbia and the southern Yukon are shown in Figs. 23 to 26. The spectra are of the first minute of the vertical component of the P wave arrival from the records of the LRSM stations in this area.

The calculated spectral decrements are shown in Table 18 and in Figure 21 as a function of the Long Shot magnitude residuals at the station.

Table 18. Long Shot Spectral Decrements

station	distance (°)	Long Shot mag. res.	spectral decr. β (sec/cycle)	95% conf. limits
Adak Is.	2.6	(+ .9)	3.3	± .7
Burwash Landing	24.7	- .3	3.8	± .6
Whitehorse	26.6	-1.1	3.8	± .8
Watson Lake	29.8	- .6	3.5	± .6
Smithers	31.8	-1.1	3.0	± .4
Fort Nelson	33.0	- .6	3.8	± .5
Prince George	34.6	-1.3	4.5	± .6
Victoria*	36.2	- .6	4.3	±1.0
Keg River	36.4	- .4	4.0	± .6
Jasper	37.4	- .6	4.2	± .6
Rocky Mt. House	39.4	- .3	7.2	±1.3
Leduc	39.9	+ .1	4.4	± .8
Blue Mt. Observatory	41.7	- .4	4.3	± .8
Sweetgrass	42.7	- .2	3.4	± .9

Jensen et al (1966)

The average spectral decrement at the stations in the anomalous region is 3.9 as opposed to an average of 4.4 for stations outside of it. The spectral decrement does not reflect the anomalous magnitude residuals in the manner that would be expected in that the larger, average spectral decrement is associated with stations with small magnitude residuals.

The spectral decrement appears to increase in proportion to distance from the source (Fig. 22) as would be expected. The relationship, if real, is largely obscured by the large scatter and particularly, by the small spectral decrement at Sweetgrass.

Although the spectral decrement does not appear to differ significantly from the mean at stations recording anomalously low Long Shot amplitudes, the large scatter of the results could easily obscure any variation that might have been expected.

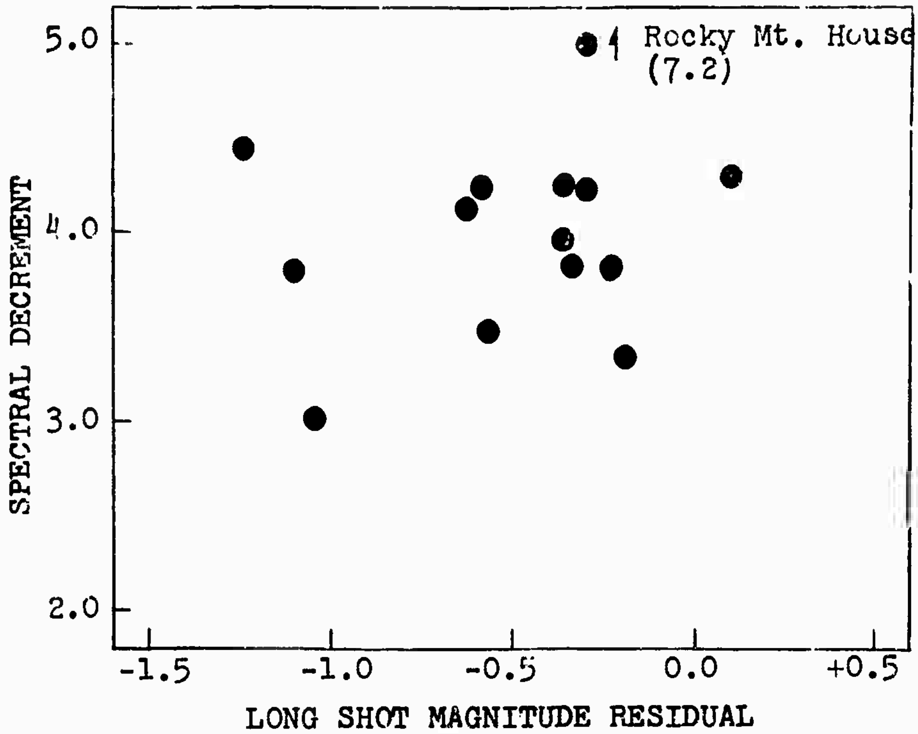


FIGURE 21. Long Shot spectral decrements versus magnitude residuals.

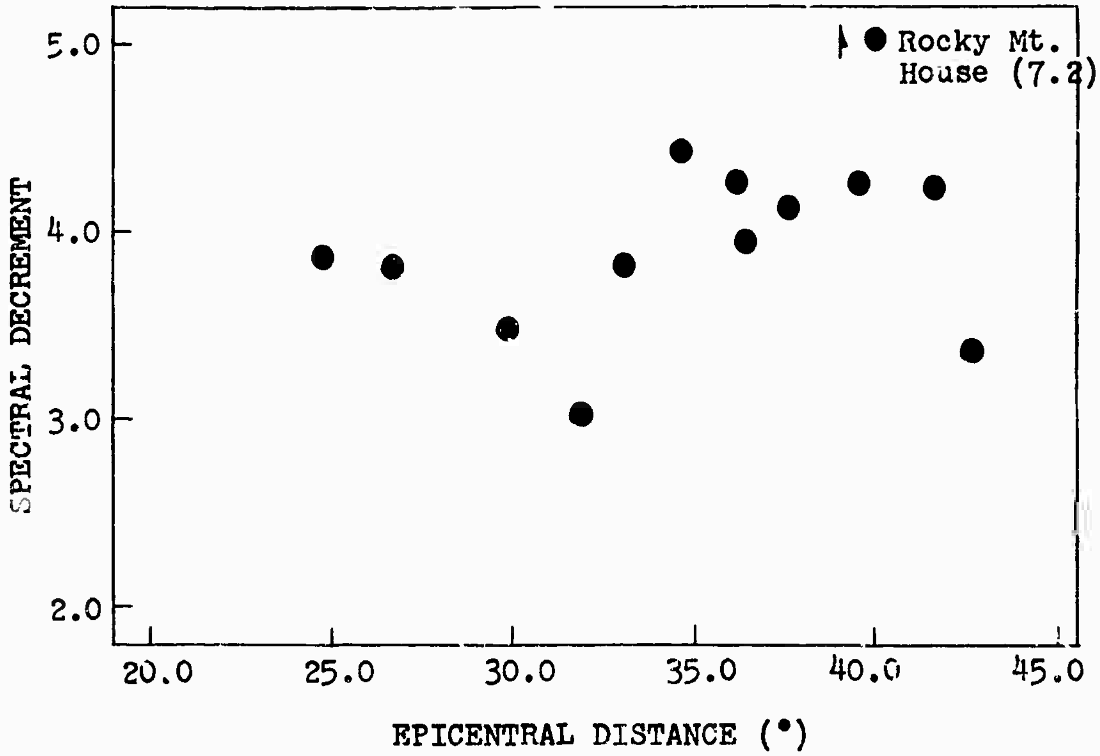
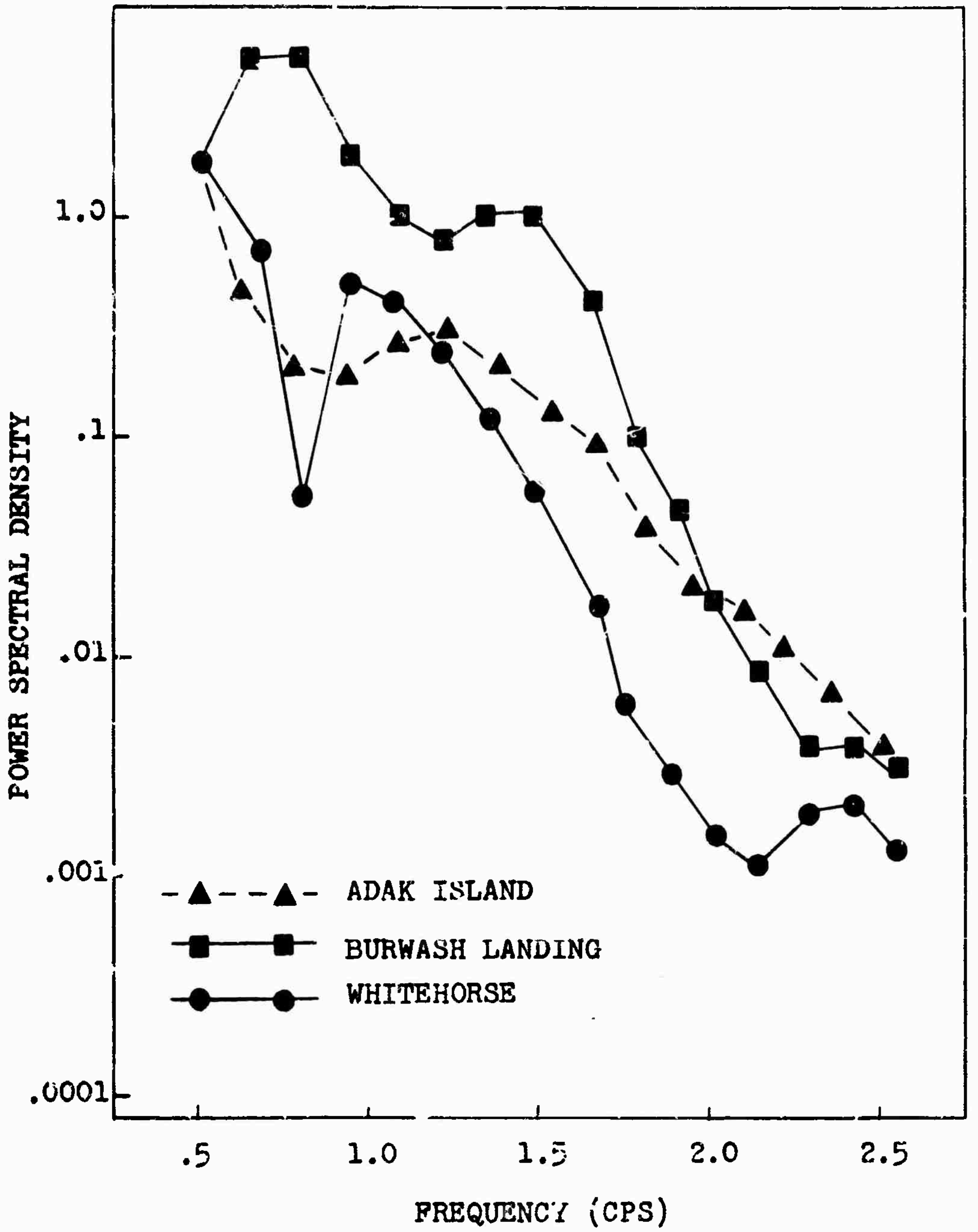


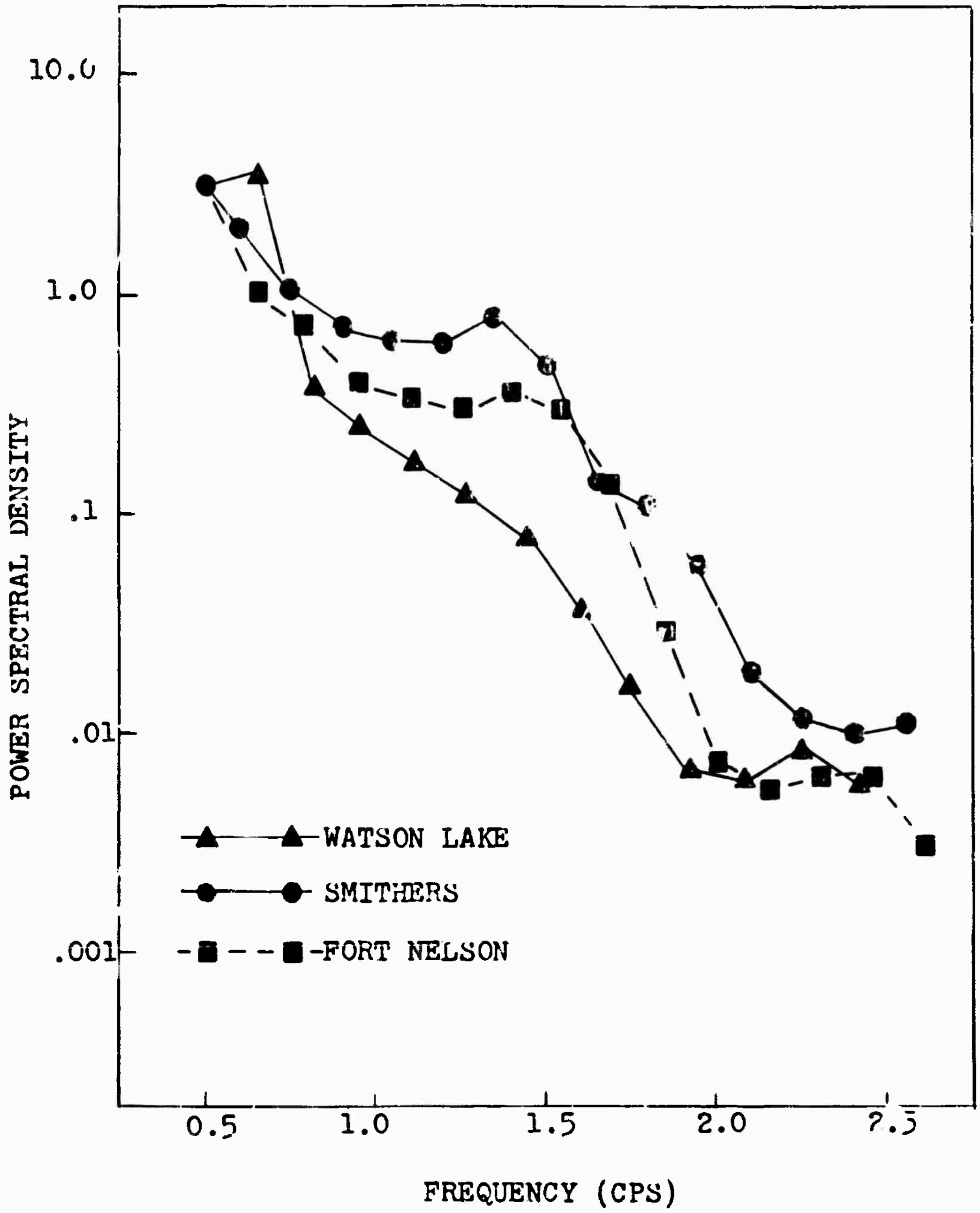
FIGURE 22. Long Shot spectral decrements versus epicentral distance.



Power spectral density at 0.5 cps (microns^2/cps)

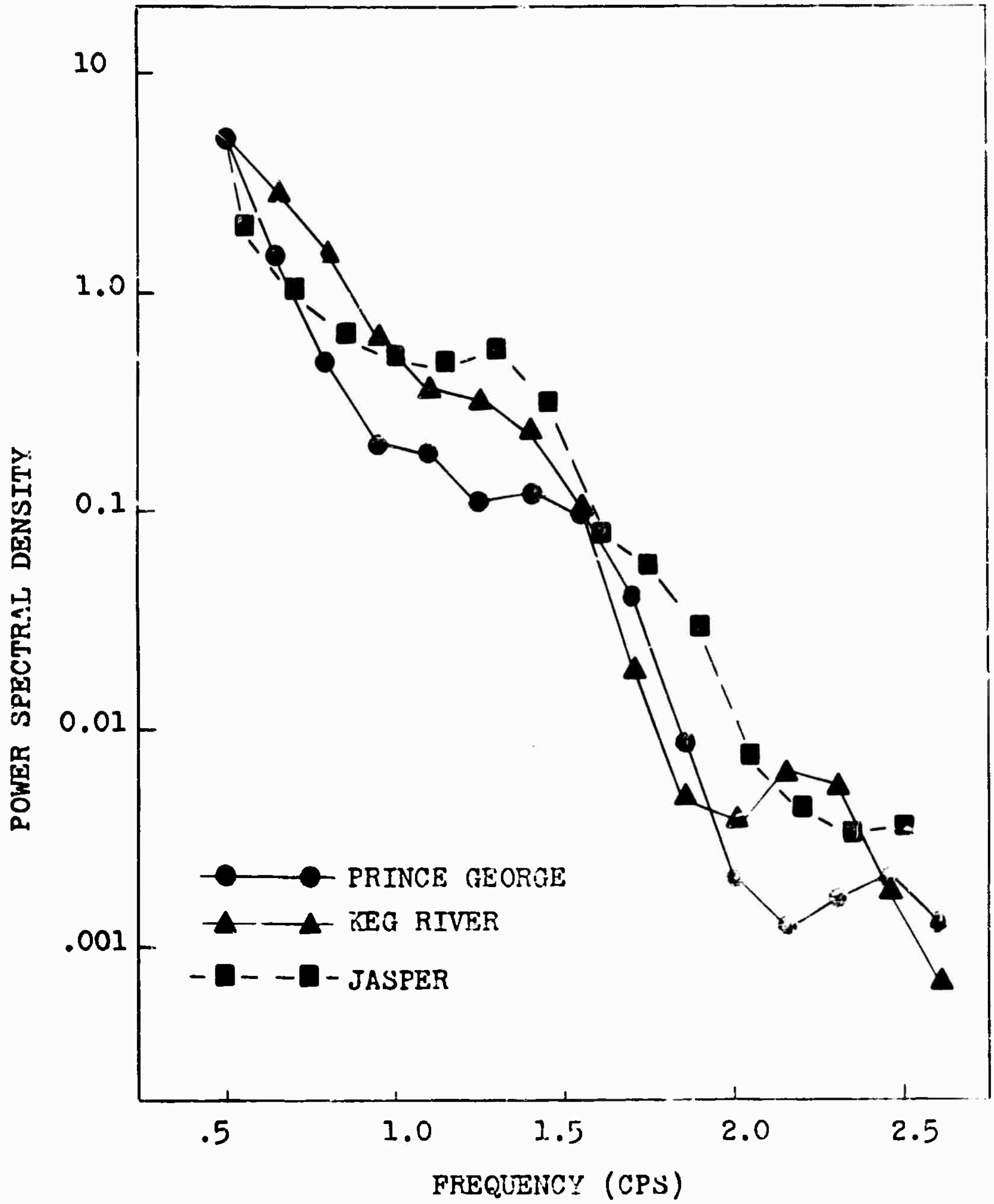
Adak Island	1000
Burwash Landing	25
Whitehorse	18

FIGURE 23. Long Shot spectra at Adak Island, Burwash Landing and Whitehorse.



Power spectral density at 0.5 cps (microns^2/cps)	
Watson Lake	5
Smithers	24
Fort Nelson	19

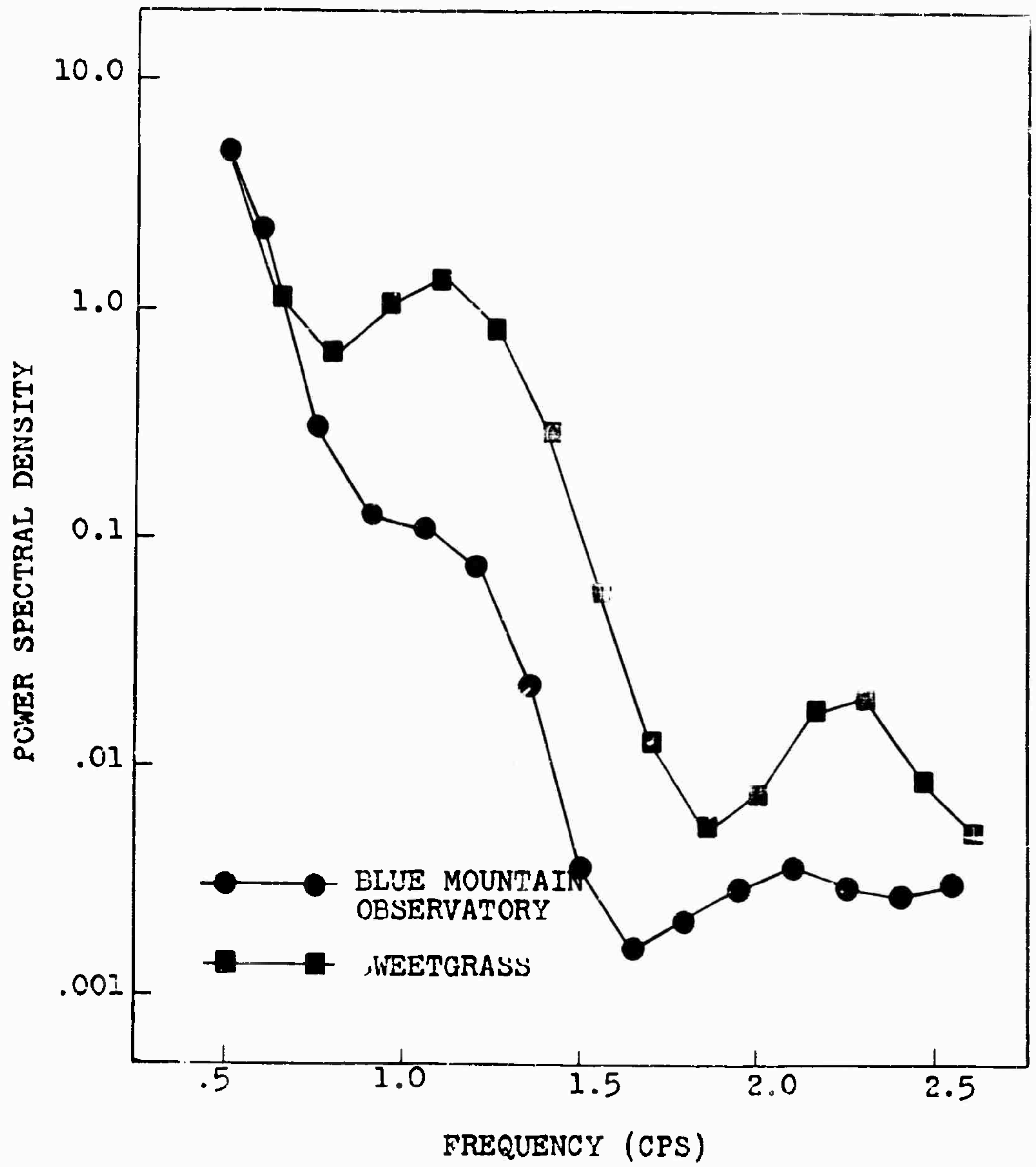
FIGURE 24. Long Shot spectra at Watson Lake, Smithers and Fort Nelson.



Power spectral density at 0.5 cps (microns^2/cps)

Prince George	5
Keg River	30
Jasper	20

FIGURE 25. Long Shot spectra at Prince George, Keg River and Jasper.



Power spectral density at 0.5 cps (microns^2/cps)

Blue Mountain Observatory	100
Sweetgrass	2

FIGURE 26 · Long Shot spectra at Blue Mountain Observatory and Sweetgrass.

CHAPTER V

CONCLUSIONS

On a regional basis, the Long Shot residuals are compatible with an amplitude-tectonic zoning in which the magnitude residuals tend to be relatively negative and arrivals late in regions of recent orogeny, while positive magnitude residuals and early arrivals characterize stations in stable regions. These trends are consistent with those indicated by data from other seismic sources.

The mean magnitude residuals for earthquakes of 0.17 ± 0.03 at Penticton and -0.14 ± 0.05 at Fort St. James compare with the Long Shot residuals of 0.0 and -0.8 at these stations; that is, the amplitudes at Penticton tend to be higher than at Fort St. James. The mean magnitude residual for earthquakes of 0.36 ± 0.08 at the University of British Columbia is markedly different than the Long Shot residuals of -0.6 observed at Victoria and Port Hardy which are in a comparable tectonic environment. At least part of this difference can be explained by the relative amplification due to the low velocity and low density sedimentary material upon which the University of British Columbia station is situated.

Magnitude residuals from the two types of sources were more similar if the earthquake data were restricted to events in the Aleutian Arc region. At all three stations, the earthquake magnitude residuals tended to be less than the mean for events with distance and azimuth comparable to Long Shot. The systematic variations with distance of the earthquake magnitude residuals at these stations suggests the need for modifications to the standard amplitude-distance relationships as well as the possibility of lateral

inhomogenieties beneath the stations.

The mean earthquake time residuals of 0.17 ± 0.13 sec at Penticton and 0.54 ± 0.26 sec at Fort St. James are compatible with the Long Shot residuals of -3.9 and -2.7 sec at these stations to the extent that the arrivals at Penticton tend to be early with respect to arrivals at Fort St. James. The consistently negative Long Shot travel time residuals indicate a strong regional bias that is probably due to an anomalously high upper mantle velocity in the Aleutian Arc region. The earthquake time residuals at Penticton and Fort St. James indicate a similar bias, as the residuals from events in that region were most similar to the Long Shot residuals.

The mean earthquake magnitude residual of -0.14 ± 0.05 at Fort St. James supports the suggestion that it is located in a region of anomalously low amplitude. As the mean residuals at Penticton, The University of British Columbia, Port Hardy and Victoria are all greater than zero, these stations must be excluded from the region despite gross similarities to the tectonic environment of Fort St. James. H. I. S. Thirlaway (private communication) has observed that mountainous regions generally give low amplitudes which are probably caused by scattering of the P wave within the crust and in the vicinity of the station, La Paz, Bolivia being an extreme example. This mechanism probably contributes to the low amplitude region in central British Columbia and the southern Yukon.

Reliable or tentative surface wave identifications have now been made at 14 Canadian stations (Currie et al; 1967) as compared with the 16 stations reported by Liebermann et al (1966) and the 5 stations initially reported by Jensen et al (1966) Long Shot has been found to be an inefficient generator of surface waves

relative to an earthquake of comparable magnitude. A unified magnitude of only 5.1 is indicated by surface waves as opposed to a magnitude of 6.0 from body waves. This is consistent with observations made of other underground nuclear explosions.

Earthquakes exhibited larger spectral decrements than Long Shot at Leduc and Victoria. That is, there was relatively more energy at high frequencies in the Long Shot signal than in the signals of the earthquakes considered at these stations. The earthquake spectral decrements varied from station to station in a manner similar to the variations of the Long Shot spectral decrements which is indicative of a near station effect.

The spectrum of Long Shot at Rocky Mt. House appeared to be anomalous in that its spectral decrement was larger than that of Long Shot at the other stations and, on the average, indistinguishable from the spectra of earthquakes recorded there.

The variation in Long Shot spectral decrements between stations in and around the anomalous region in central British Columbia and the southern Yukon could not be correlated with the low amplitude region despite the fact that spectral decrement is partially determined by near station s' ucture.

The effect of the source parameters was indicated by a weak tendency for the spectral decrement to decrease with decreased distance to source and with increased depth. Events from the 140° azimuthal zone also tended to exhibit spectral decrements less than the mean.

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13. ABSTRACT

The seismic signal generated by the underground nuclear explosion, Long Shot, has been compared with seismic signals of earthquake origin and found to be similar on a regional scale. Negative Long Shot magnitude residuals are associated with areas of recent tectonic activity as are late arrivals, while positive Long Shot magnitude residuals and early arrivals have been found to be associated with tectonically stable regions. These trends are coincident with those indicated by data from other seismic events.

The more detailed comparison of Long Shot and Earthquake magnitude residuals at Penticon and Fort St. James indicates that the Long Shot residuals also reflect the location of the source. At these stations earthquakes with distances and azimuths comparable to Long Shot exhibit magnitude residuals that are most similar to those of Long Shot. The magnitude residuals of the University of British Columbia exhibit the same dependence on source parameters although a direct comparison with Long Shot could not be made. An examination of earthquake travel time residuals at Penticton and Fort St. James also indicates the same dependence on source location.

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(ABSTRACT Continued)

Long Shot surface waves indicate an average unified magnitude of 5.1 at Canadian stations as compared with an average unified magnitude of 6.0 from body waves at the same stations.

The comparison of the power spectra of Long Shot and earthquakes at Leduc and Victoria indicates relatively more energy at high frequencies from Long Shot than from earthquakes. This variation in spectral decrement is interpreted as an effect of the different source mechanisms.

The spectrum of Long Shot at Rocky Mt. House appeared to be anomalous as it had a significantly larger spectral decrement than at the other stations and was indistinguishable from the spectra of earthquakes recorded at Rocky Mt. House. The trend of the power spectra also appear to be partially determined by the crustal and upper mantle structure in the vicinity of the station. The effect of the source parameters and travel path is also indicated by a tendency for the spectral decrement to increase with increased distance to source and with increased depth.